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

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Graduate Program in Kinesiology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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Abstract

The use of combined anterior cruciate ligament (ACL) plus lateral extra-articular tenodesis (LET) reconstruction has shown promising results during clinical testing, however, no studies have examined its effectiveness during a dynamic functional task. We used the drop vertical jump (DVJ) to compare *in vivo* biomechanics of ACL reconstructed patients with and without LET.

Our primary outcome was peak knee abduction moment during stance phase. Secondary kinetic and kinematic outcomes included peak initial contact and stance values for knee abduction angle, knee flexion moment and angle, knee internal rotation moment and angle, and vertical ground reaction force. We also assessed fear associated with physical activity between patients who were and were not able to perform the DVJ test.

We found no significant differences between treatment groups at six months postoperative. This thesis presents the preliminary results of a continuing study and at this time no definitive conclusions can be made.

Keywords

Anterior cruciate ligament, ACL, anterior cruciate ligament reconstruction, lateral extra-articular tenodesis, LET, drop vertical jump, DVJ, fear avoidance beliefs, FABQ

Co-Authorship Statement

This study was organized with collaborative input from Dr. Alan Getgood, Dr. Dianne Bryant, Dr. Trevor Birmingham and Sheila Gagnon. We designed a prospective study as an extension of a larger ongoing multicenter randomized clinical trial. I was responsible for data collection, analysis and writing of the original draft of the manuscript. Dr. Bryant and Dr. Getgood provided me with suggestions and comments towards the final thesis submission. The preliminary manuscript was also sent to Mrs. Sheila Gagnon for her comments and suggestions towards the biomechanical aspect of the study.

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List of Abbreviations

ACL	Anterior cruciate ligament
LET	Lateral Extra-Articular Tenodesis
DVJ	Drop vertical jump
KAM	Knee abduction moment
FABQ-PA	Fear Avoidance Beliefs Questionnaire – Physical Activity Subsection
VGRF	Vertical ground reaction force
IC	Initial contact
TO	Toe off
%BW×ht	Percent body weight times height
KAA	Knee abduction angle
KFA	Knee flexion angle
KRA	Knee rotation angle
KFM	Knee flexion moment
KRM	Knee rotation moment

Chapter 1

1 Introduction

The aim of anterior cruciate ligament (ACL) reconstruction is to regain functional knee stability following ACL injury.¹ As the sixth most commonly performed procedure in orthopaedic surgery, the ACL reconstructive technique has evolved significantly since the early 1900's when it was first performed.^{2,3} However, recent studies have shown that graft failure and anterolateral instability rates remain high among conventional isolated ACL reconstructions.⁴⁻⁶

Biomechanical evaluations of traditional ACL reconstruction have demonstrated limitations in restoring normal knee stability.⁷⁻¹¹ Although the more commonly performed transtibial procedures have demonstrated adequate control of antero-posterior tibial translation, some studies have noted abnormal tibial rotation in the transverse plane when compared to the contralateral knee.^{7,12-14} Several researchers have linked these biomechanical instabilities to an associated injury of the anterolateral capsule, suggesting that augmentation of the ACL reconstruction with an extra-articular graft may provide improved knee stability in patients at high risk of graft failure.¹⁵⁻¹⁹

Over the last few years, journals have shown an increasing interest in combining ACL reconstruction with extra-articular augmentation.^{1,20} Several papers have shown support for this technique by demonstrating that the additional reconstruction not only protects the graft from excessive loads, but also improves lateral rotational control.^{19,21-24} Among the surgical techniques documented in the literature, the lateral extra-articular tenodesis (LET) has reported excellent clinical results.^{23,24} However, its ability to control dynamic knee stability during a pragmatic functional task has yet to be assessed.

To our knowledge, there has been no prior research evaluating *in vivo* biomechanics following a combined intra-articular ACL reconstruction with lateral extra-articular tenodesis. This study will answer important questions regarding the dynamic, functional stability of the combined ACL plus LET reconstruction when compared to conventional ACL reconstruction alone.

Chapter 2

2 Literature Review

2.1 Knee Anatomy

Primarily allowing for flexion and extension, the knee is a hinge-type synovial joint that provides our lower body with the fundamental movements of human locomotion. It is composed of three bony articulations: two-tibiofemoral articulations between the tibial plateau and both medial and lateral femoral condyles, as well as one patellofemoral articulation between the posterior surface of the patella and the anterior surface of the distal femur.²⁵ Due to the non-complementary fit between the surfaces of these articulating bones, the knee's stability is entirely dependent upon its surrounding muscles and ligaments.²⁶

As dynamic stabilizers, the primary muscles that provide support for the knee joint include the following: (1) quadriceps femoris and extensor retinaculum, (2) pes anserinus (semitendinosus, sartorius and gracilis), (3) popliteus, (4) biceps femoris and semimembranosus.²⁷

The passive stabilizers of the knee include the joint capsule, the menisci and various ligaments.²⁷ The knee joint capsule consists of an alternating thick and thin fibrous layer internally lined by a synovial membrane.²⁵ The capsule itself is strengthened by five extracapsular ligaments: the fibular/lateral collateral ligament (LCL), the tibial/medial collateral ligament (MCL), the patellar ligament, the oblique popliteal ligament and arcuate popliteal ligament.²⁵ In addition to its external support, the knee is also passively stabilized by two sets of intracapsular structures including two fibrocartilagenous menisci and two cruciate ligaments: the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL).²⁵ The menisci (medial and lateral) are two crescent shaped fibrocartilages located on the superior articular surface of the tibia.^{25,26} They play a role in shock absorption at the knee and act to deepen the tibial surface on which the femoral condyles sit thereby distributing load.²⁵ The cruciate ligaments are located in the center of

the knee joint and cross each other obliquely, like the letter “X”.²⁵ Together, they act primarily to limit anterior and posterior translation of the tibia with respect to the femur.²⁸

2.2 The Anterior Cruciate Ligament (ACL)

2.2.1 Anatomy

The ACL originates from the postero-medial aspect of the lateral femoral condyle and descends anteriorly, distally and medially towards its insertion on the anterior intercondylar area of the tibia.^{28,29} Over the length of its course, the fibers of the ligament undergo slight external rotation as they cross anterolateral to the posterior cruciate ligament.²⁹ Cadaveric studies have established the ACL to have an average length and width of 38mm and 11mm respectively, although these dimensions vary throughout knee flexion and extension as the ligament becomes relaxed and taut.^{28,29}

It has been well documented that the ACL is divided into two separate bundles: the anteromedial (AM) and the posterolateral (PL) bundle.²⁸⁻³¹ The classification of these anatomically and functionally distinct bundles is based on their tibial insertion sites as well as their orientation and tensioning patterns throughout the range of motion of the knee.²⁸⁻³¹

2.2.2 Tissue Mechanics

The ACL is the primary static stabilizer against anterior tibial translation with respect to the femur.^{28,29} Many studies have investigated the ACL’s tensile properties, but its complex structure makes it difficult to load all ligament fibers uniformly.³² Investigators have therefore tested each of the ACL’s bands separately, allowing them to make conclusions about their individual mechanical properties and ultimately understand their contributions to knee stability.^{31,32} The ACL’s AM and PL bundles stabilize the knee joint in varying proportions throughout the different stages of knee motion.³¹ The anteromedial bundle becomes tightest between 60 and 90 degrees of flexion, whereas the

posterolateral bundle becomes taut as the knee approaches full extension.^{29,31} The literature also suggests that the ACL plays a secondary role in resisting both internal tibial rotation and tibial abduction with respect to the femur.^{28,29,33-35}

2.3 Mechanism of Injury

ACL injuries can be classified into one of two categories: contact (the result of an external force applied either directly or indirectly to the patients knee), and non-contact (the result of the athletes own movement, in the absence of any external forces other than ground reaction force).³⁶⁻³⁸

Between 70-80% of all ACL injuries occur in non-contact situations,^{39,40-43} typically when landing from a jump, cutting or decelerating, although many studies have suggested a combination of movements.^{37,41} Common playing situations which lead to ACL injury include: (1) a cutting maneuver or rapid change in direction combined with deceleration, (2) a pivot with the knee near full extension or (3) a combination of deceleration with dynamic valgus with the body weight shifted over the planted foot.^{42,44} Of all the mechanisms suggested, the most prevalent mode of injury involves a combination of knee valgus and internal tibial rotation.^{36,45,46} Cadaveric studies by Markolf et al. and Fukuda et al. have confirmed this mechanism by showing that combined tibial internal rotation moment and valgus moment significantly increase forces through the ACL.^{47,48} These results are also consistent with the pivot shift test method which is meant to recreate the “giving way” that occurs during ACL injury.^{49,50}

In addition to the movement patterns listed above, there are also a number of extrinsic factors (those outside the body) and intrinsic factors (those within the body) which predispose certain individuals to a higher likelihood of ACL injury.^{37,51} Extrinsic factors are modifiable (within the athletes control) and include footwear, playing surface, type of sport and level of competition. Intrinsic factors can also be modifiable or they can be non-modifiable (completely out of the athletes control).^{42,43} Modifiable intrinsic factors include body mass index (BMI), neuromuscular and biomechanical deficits and fatigue,

whereas non-modifiable intrinsic risk factors for ACL injury include female gender, narrow femoral notch width, ligamentous laxity and genetic predisposition.⁴³

2.4 Epidemiology

It has been estimated that the knee accounts for 19-23% of all musculoskeletal injuries.⁵² Of these injuries, the ACL is one of the most commonly damaged structures, effecting between 100,000 and 250,000 Canadians and Americans annually.^{31,53} In addition to the personal burdens of pain, extensive rehabilitation and lost productivity, it is estimated that ACL injuries also carry a financial healthcare cost of \$1-2US billion annually.^{40,54}

Several national registries have recorded the number of annual surgical reconstructions and their outcomes.³⁸ In 2009, Lars-Petter Granan and colleagues published the results of three Scandinavian (Norway 2004, Denmark 2005, and Sweden 2006) national registries.⁵⁵ Specifically, Norwegian data from 57 hospitals documented a total of 2793 primary ACL reconstructions during an 18 month period,⁵⁶ which corresponds to an annual population incidence of 34 primary ACL surgeries per 100,000 citizens.⁵⁶ After analyzing the data in more detail, researchers found that the main at-risk age group of 16-39 years had an incidence of 85 per 100,000 citizens.⁵⁶ Similar incidence was noted for Sweden and Denmark who reported an annual incidence of ACL reconstruction of 32 per 100,000 citizens and 38 per 100,000 respectively.^{55,57} Once again, ACL reconstructions were much more common for the at-risk age group in Sweden (20-39 year) and Denmark (15-39 year) showing an annual incidence of 71 and 91 per 100,000 inhabitants respectively.^{55,57} Although these studies can be used to estimate the incidence of ACL injury, the incidence is underestimated as non-operatively managed patients are not captured within the registry.

More recently, in 2016, Sanders et al. published a 21-year population-based study on incidence of ACL tears and reconstructions in the United States. Between January 1, 1990 and December 31, 2010, 1,841 individuals were diagnosed with new-onset, isolated ACL tears (without concomitant ligament injuries). The overall sex- and age-adjusted

annual incidence of ACL tears was 68.6 per 100,000 person-years with male patients demonstrating significantly higher rates than their female counterpart (81.7 versus 55.3 per 100,000, $P < 0.001$).⁵⁸

2.5 Incidence in Specific Groups

There is a growing consensus that the ACL mechanism of injury is multifactorial, occurring as a result of mechanical, morphologic and neuromuscular factors combined.⁵⁹ Research in the field of orthopedic sport medicine has used these factors to identify at-risk populations.³⁸ Investigators have found that ACL injury rates are age, gender and sport specific.^{38,60}

As identified in the Scandinavian registry review by Granan et al., the most operated upon citizens in Norway and Sweden were in the 10-19 years age group.⁵⁵ Denmark had a higher average age of injury (27) and surgery (30), with the most surgeries being performed on individuals aged 20-29.⁵⁵ An earlier study from 2002 by Yu et al. analyzed the number of ACL reconstructions performed by candidates for certification before the American Board of Orthopedic Surgeons. They found that the highest number of ACL injuries occurred in ages 16-18 years.⁶¹ These findings are specific to reconstruction not injury, therefore they do not account for individuals who underwent non-operative management. These numbers do however provide insight into the age specific incidence of ACL reconstruction in the U.S. population.

Several studies have also investigated the occurrence of ACL injuries among males versus females. Although it varies from study to study, there is a general understanding that females are much more likely to sustain an ACL injury than their male counterpart. A 2014 study by Beynnon et al. looked at the effects of sex, sport and level of competition on the incidence of non-contact first time ACL injury. A total of 26 institutions (8 colleges and 18 high schools) participated between fall 2008 and spring 2012. During that time, colleges reported 48 first-time non-contact ACL injuries following 320,719 athlete exposures and high schools reported 53 injuries with 873,057

exposures. After adjustment for sport and level of play, the authors found that females were more than twice as likely (relative risk (RR) of 2.10) to have a first time ACL injury compared to males.⁶²

An earlier study by Mountcastle et al. also looked at gender differences in ACL injury for a variety of physical activities. Ten high school graduating classes were followed between 1994 and 2003, and out of the 11,340 students shadowed, 353 had sustained an ACL injury (an overall 4-year incidence proportion of 3.24 per 100). Results showed that, after excluding male-only sports, the overall ACL injury rate was significantly higher among women than among men (incidence rate ratio, 1.51). The authors also looked at the incidence of injury in specific sports and activities, and discovered even higher injury rates among women in in gymnastics (incidence rate ratio, 5.67), indoor obstacle activities (incidence rate ratio, 3.72) and basketball (incidence rate ratio, 2.42).⁶³

In 2007, Prodromos et al. reviewed the entire applicable literature to generate a more accurate estimate of the true ACL tear rate as a function of gender and sport. Using a literature search through PubMed, 25 useable articles with a total of 41,252,578 athletic exposures were identified and analyzed for incidence data. Prodromos concluded that female subjects had a roughly three times greater incidence of ACL tears in basketball and soccer than their male counterparts and females who played these sports year-round had an annual tear rate of approximately 5%.⁶⁴ These findings are consistent with Hewett et al. who found a 4.4% 1-year incidence of ACL tear in a similar group of female soccer and basketball players.⁶⁵

2.6 Diagnosing the ACL Injury

The first step in evaluating any patient presenting with a suspected ACL injury is a thorough history and physical examination. Although imaging plays an important role in the diagnosis of most musculoskeletal injuries, a recent study by Geraets et al. demonstrated that orthopaedic surgeons were able to recognize 94% of all ACL injuries through positive medical history and physical examination alone.⁶⁶ Garaets evaluated the

diagnostic value of a medical history and found that four statements were statistically significant predictors of ACL injury: (1) hearing a “pop” or “snap” ($p = 0.01$). Additional research has shown that 33-90% of patients presenting with an ACL tear experienced a “popping” sensation at the time of injury and were unable to continue athletic participation;⁶⁷ (2) effusion in the first 24 hours ($p = 0.01$). Due to its capsular structure, an acute ACL will present with rapid swelling or hemarthrosis soon after the injury; (3) complaints of giving way ($p = 0.01$) and (4) having an unstable feeling in the knee ($p = 0.04$).⁶⁶ As with any history, the physician must also look beyond the knee and assess the patient as a whole. Age, sport and activity level will all influence the physician’s judgment in determining the most appropriate course of action.

The physical examination typically consists of inspection, palpation and assessment of knee joint function through a series of clinical tests. The most commonly used diagnostic assessments include the Lachman test, the anterior drawer test and the lateral pivot shift test. Each examination is used to evaluate ligament integrity with a focus on pain, laxity and endpoint. Intact ligaments will produce a firm and abrupt end-feel, whereas sprained or torn ligaments will have soft or indistinct endpoints.

2.6.1 The Lachman Test

Of the three most commonly utilized evaluations mentioned above, the Lachman test is the clinical gold standard of choice for most physicians. In 2003, Scholten et al. conducted a meta-analysis to evaluate the accuracy of ACL-specific physical diagnostic tests and concluded that the Lachman test had a sensitivity and specificity of 0.86 (95% CI, 0.79-0.96) and 0.91 (95% CI, 0.79-0.96) respectively.⁶⁸ The test is performed with the knee relaxed and passively flexed between 20 and 30 degrees. Grasping the knee above and below the joint line, the examiner applies an anterior force to the proximal tibia while stabilizing the distal femur with the contralateral hand. Excessive proprioceptive or visual anterior translation of the tibia below the femur, with a soft or mushy endpoint represents a positive result and is indicative of an ACL deficient knee.⁶⁹ The examiner grades the injury on a scale of 1 to 3, depending on the amount of laxity when compared to the

contralateral side (grade 1; 1 to 5 mm increased translation, grade 2; 6 to 10 mm increased translation and grade 3; 11 to 15 mm increased translation).^{70,69} It is important to note, however, that contralateral comparisons are made with the assumption that the uninjured side is a healthy control. This is not always the case among an active population with a history of previous injuries. It exemplifies the importance of a thorough subjective evaluation before making any conclusions about the integrity of the injured ligament.

2.6.2 The Anterior Drawer Test

The anterior drawer test is similar to the Lachman test in that it also evaluates anterior translation of the tibia with respect to the femur. The major difference between the two evaluations is the starting position from which the test is administered. Unlike the Lachman test, the anterior drawer requires the supine patient to flex their knee to 90 degrees from which the anterior force, in line with the joint line, is applied on the proximal tibia. The 90 degree flexion requirement has been reported as a test limitation and impracticality, especially when dealing with an acutely injured or swollen knee.⁶⁹ Hamstring spasm and secondary stabilization by the MCL may also limit anterior translation and ultimately produce false negative results when compared to the uninjured knee.⁷¹ These limitations are reflected in the pooled results from the meta-analysis by Scholten et al., who showed that the anterior drawer test has a sensitivity of 0.62 (95% CI, 0.42-0.78) and a specificity of 0.88 (95% CI, 0.83-0.92).⁶⁸ Grading endpoint is similar to that of the Lachman (Grade 1: 5 mm; Grade 2: 5 to 10 mm; Grade 3: >10 mm) however the testing method offers an advantage over the Lachman test when assessing the amount of laxity.⁷¹ Thumb placement on the anterior joint line (with the distal thumb on the femoral condyles and proximal thumb on the superior aspect of the tibia) allows the examiner to more objectively assess tibial translation while also avoiding misdiagnosis in a PCL-deficient knee.⁶⁹

2.6.3 The Lateral Pivot Shift Test

The lateral pivot shift test has been reported by Scholten et al. as the most specific of all three ACL tests (with a specificity of 0.97-0.99 and sensitivity of 0.18-0.48), but is also noted as the most difficult to perform.⁶⁸ As a test of anterolateral rotational laxity, the lateral pivot shift was designed to reproduce the subjective description of a patient's knee "giving out" during an attempt to change direction.⁶⁹ Starting in knee extension, the examiner will passively flex the patient's knee while simultaneously maintaining a valgus and axial load with the tibia internally rotated.⁷¹ In an ACL deficient knee the tibia will be anteriorly subluxated under the femur in its initial starting position, but will spontaneously reduce as the knee reaches 30 to 40 degrees of knee flexion.^{66,71} The primary challenge in performing this test correctly is getting the patient to relax their leg.⁶⁹ Awake and alert patients have reported the test sensation to be unpleasant and will typically guard against the movement.⁶⁶ Depending on the subtlety of the reduction, the examiner will grade the injury on a scale of 0 to 3; grade 0 if no shift is present; grade 1 if the tibia glides smoothly as it reduces; grade 2 if the tibia clunks back into place; and grade 3 if the tibia transiently locks before reduction.^{69,70}

2.6.4 Imaging

Radiographs have little value when diagnosing soft tissue injuries of the knee, although, they can be useful in identifying indirect signs of an underlying ACL tear.⁷² One of the most commonly identified x-ray findings in a suspected ACL injury is the Segond fracture.^{15,73} Diagnosed as an anterolateral capsular avulsion fracture of the lateral tibial rim, the Segond fracture has shown a strong association with ACL injury (75-100%).^{15,16}

Another useful method of evaluation is magnetic resonance imaging (MRI). Unlike an x-ray, MRI has the advantage of detecting soft tissue and therefore provides a direct method of assessing ACL damage.^{72,74-76} Several investigators have compared MRI findings to diagnostic arthroscopy and found that the accuracy of ACL imaging ranged from 90% to 100%.⁷⁷⁻⁸⁰ In 1996, Rose et al. conducted a study comparing the accuracy of

clinical examination to MRI in diagnosing meniscus and ACL tears. Of the 154 patients who underwent arthroscopic knee surgery, 100 patients underwent both clinical examination and MRI (54 underwent clinical examination alone). The presence or absence of a true ACL injury was confirmed during arthroscopy and results showed that the accuracy of MRI was 98% for ACL tears, compared to clinical examination which showed an accuracy of 99%.⁷⁵ These findings confirm the notion that, although MRI is an accurate, noninvasive method of evaluating ACL injury, it is no more accurate than the more cost effective alternative of clinical examination for this specific injury.

2.7 Treatment

2.7.1 Surgical vs. Non-Surgical Management

The decision to manage an ACL rupture operatively or non-operatively depends on several factors: degree of knee stability, pre injury level of activity, fear of not being able to return to a previous level of physical ability, age and patient preference.^{81,82} Non-operative management consists of physical therapy, activity modification and bracing.⁸¹ It is typically the recommended treatment option for sedentary or less active individuals. Operative management, on the other hand, is recommended for active individuals who plan to resume high level physical activities requiring movements like jumping, cutting, or pivoting.⁸¹ Both treatment methods have reported good clinical outcomes in short and long term followups.⁸¹

In 2010, Frobell et al. conducted a randomized control trial consisting of 121 young (aged 18 to 35 years), active adults with acute ACL injury to determine the optimal method of management following ACL tear.⁸³ Patients were randomized to receive an ACL reconstruction combined with structured rehabilitation or structured rehabilitation alone with the option of later ACL surgery if needed. Of the 59 subjects who received the rehabilitation alone, 23 went on to undergo an ACL reconstruction while the other 36 chose to continue with non-operative management. Results also showed no significant difference between groups in Knee Injury and Osteoarthritis Outcome Score (KOOS) for

pain, symptoms, function in sports and recreation, and knee-related quality of life. These findings demonstrate that early surgery provides no added benefit over delayed surgery with the option to undergo rehabilitation alone. However, a greater number of patients in the delayed surgery group had sustained meniscal injury by the time they had their surgery which could have implications for the development of OA in the future.

A number of researchers have also investigated the long-term outcomes of operatively and non-operatively managed ACL injuries, though their conclusions are limited by the retrospective nature of their studies. Kessler et al. (2008), Meuffels et al (2008) and Streich et al. (2010) looked at the long term (11 year, 10 year and 15 year respectively) effects of ACL injury and concluded that there is no significant difference between operative and non-operative management.⁸⁴⁻⁸⁶ All three studies acknowledged that operatively treated ACL injuries were more stable at long term follow-up, but subjective findings showed no difference between the two groups. Kessler et al. even stated that operatively managed ACL tears were more likely to develop osteoarthritis (OA) than their non-operatively managed counterpart, although these results were not statistically significant ($P = 0.16$).⁸⁴ Since the studies were not randomized, it is important to note that these findings may be the result of appropriate patient selection with regards to treatment option. Active patients are more likely to be treated operatively in an effort to control stability, whereas less active patients may benefit more from conservative management.⁸¹ These inherent group differences in activity level likely explain the similarity in satisfaction and the increased likelihood of OA development in the surgically managed group.

2.7.2 Surgical Treatment Options

As the sixth most commonly performed procedure in orthopaedic surgery, the ACL reconstruction is a heavily investigated method of treatment and although it is widely accepted, the surgical procedure continues to evolve.² Whether it's the graft tissue selection, the type of fixation or the use of a single- vs. double-bundle, the method of reconstruction is heavily dependent on surgeon preference, previous surgical history,

concomitant injuries and patient choice.^{87,88}

2.7.2.1 Graft Selection

Graft tissue can be categorized into three types: 1) allografts (cadaveric tissue taken from another human donor); 2) autografts (tissue harvested from the patient, but from a different part of the body); or 3) synthetic grafts (tissues, artificially developed using scaffold, stents or presthesis).^{87,88} Autografts and allografts have been documented as the most commonly used option for ACL reconstruction.⁸⁷

Over the past decade, the use of allografts for both primary and revision ACL surgery has become progressively more popular, however autografts remain the preferred tissue of choice.^{89,6} The primary advantage of using an allograft is the avoidance of donor site morbidity.⁶ Additionally it provides a shorter operative time (as there is no need for harvest), improved cosmesis and greater variety of tissue options and sizes.⁶

Donor tissue can consist of tibialis posterior tendon, Achilles tendon, tibialis anterior tendon, bone-patella tendon-bone (BPTB) and peroneus longus tendon.^{87,90} The major concerns, as with any allogenic tissue, are the potential for disease transmission, delayed incorporation and decreased graft strength/stiffness, depending on the processing technique used.^{87,88,91}

In 2015, Bottoni et al. published results from a 10-year randomized control trial comparing autograft (Hamstring) to allograft (tibialis posterior) and found a significant difference in failure rate between the two groups. By the end of their 10 year follow-up, graft failure was reported in 20% of their study population (of 97 patients), where those who received an allograft failed at a rate 3 times higher (26.5% failure) than those who received an autograft (8.3% failure)(RR, 3.3; 95% CI, 1.2 to 9.5).⁶

In 2014, a group of surgeons lead by Wright et al. published the results of the multicenter ACL revision (MARS) cohort and found similar rates of failure between the two graft types. The overall re-rupture rate (37/1112, 3.3%) was much lower than Bottoni et al. but

ratios of failure between autograft and allograft reconstruction were similar. Those who received an autologous graft for revision ACL surgery were 2.8 times less likely to sustain a subsequent graft rupture than those who received an allograft ($p = 0.05$; 95% CI = 1.0 to 7.7).⁹² These results are further supported in a meta-analysis by Prodromos et al. who reported an abnormal stability in 5% of all autografts versus 14% of all allografts (RR, 2.8; 95% CI, 1.1 to 7.8, $p < 0.01$).⁹

Autografts usually consist of either hamstring tendon (HT) or bone-patella tendon bone (BPTB).^{87,89} The quadriceps tendon autograft has also been documented in the literature, gaining popularity in the late 90's, although it is less commonly used than the two aforementioned graft choices. Each option has its own strengths and weaknesses, therefore surgeons will choose the graft that best suits their patient's needs. Advantages of using an HT tissue over BPTB include better extension strength and lower donor site morbidity.^{93,6,90} Disadvantages include weakness at terminal knee flexion, laxity at fixation site and graft size inconsistency.^{2,87,92,93} A BPTB autograft provides a more secure fixation, a lower failure rate and an overall higher patient satisfaction, however it also has its limitations.^{87,90,94,95,96} Patients who receive a BPTB autograft typically present with increased anterior knee pain and numbness (due to the location of the harvest site) and a greater incidence of extension loss.^{93,95}

Due to the popularity of autograft usage in ACL reconstruction, the topic of HT versus BPTB graft selection has been highly researched. The major strengths and weaknesses have been described above, but meta-analyses by Freedman et al. (2003) and more recently ShuZhen et al. (2010) have looked at the pooled differences in more detail.^{93,95} After pooling the data from 21 BPTB and 13 HT studies, Freedman concluded that there was a significantly lower rate of graft failure among patients who received a BPTB (25/1318) graft versus those who received a HT graft (23/468)(RR, 2.6; 95% CI, 0.8 to 8.6, $p < 0.001$). BPTB grafts also showed higher patient satisfaction (95% vs. 87%, $p < 0.001$) and greater static stability, shown by KT-1000 side-to-side difference $< 3\text{mm}$, when compared to the hamstring tendon (79% vs. 73.8%, $p = 0.017$). However, BPTB patients were more likely to experience complications (particularly motion problems) requiring surgical intervention, leading to an increased likelihood of anterior knee pain.⁹⁵

Seven years after the publication by Freedman et al, ShuZhen et al. conducted a similar meta-analysis focusing specifically on 19 randomized control trials comparing HT and BPTB. Similar to the earlier review, ShuZhen found that better stability, indicated by lower KT-1000 arthrometer values, favored BPTB reconstruction. However, there was no significant difference in the number of graft failures between the two groups (28/575 for HT vs. 19/591 for BPTB) (RR, 1.6; 95% CI, 0.9 to 2.9, p=0.09). Postoperative complications of the knee joint were also found to be higher among patients who received a BPTB autograft.⁹³ When comparing results from both meta-analyses there is an apparent reduction in graft failure over time, particularly among patients receiving an HT autograft. Both studies acknowledged the constant improvements in surgical fixation, particularly the application of the modern endobutton in HT ACL reconstruction, making the differences between graft choices even less apparent.^{93,95}

2.7.2.2 Double-bundle and anatomic single-bundle technique

Biomechanical studies of traditional ACL reconstruction have demonstrated limitations in restoring normal knee stability when compared to the uninjured side.^{7,8} Although the more commonly performed transtibial procedures have demonstrated adequate control of antero-posterior tibial translation, some studies have noted abnormal tibial rotation in the transverse plane.^{7,12} Studies by Georgoulis et al. and Ristanis et al. investigated knee joint mechanics during stair descent with pivoting and have concluded that traditionally placed hamstring autografts do not restore normal tibial rotation.^{7,8} The traditional transtibial reconstruction technique has also been challenged for its inaccurate tunnel placement when compared to the native ACL footprint, thus resulting suboptimal knee biomechanics.¹³ These issues have lead surgeons to reconsider the method in which the ACL is reconstructed. Recent modifications include the anatomic single-bundle reconstruction and the double-bundle reconstruction.

The goal of the anatomic ACL reconstruction is to replicate the knee's native anatomy and restore normal knee kinematics.^{8,12,97} Traditional ACL reconstruction techniques

were designed with the assumption that all ACL's are similar in size and orientation; however, a 2011 study by Kopf et al. demonstrated that there is substantial variation in the shape, size and insertion.⁹⁸ A year later, Kopf conducted another study to assess the accuracy of graft orientation in traditional transtibial arthroscopic ACL reconstruction and found that this technique fails to accurately place the femoral and tibial tunnels within the native ligament insertion sites.⁹⁹ Tibial tunnels were consistently drilled medial to the anatomic PL bundle insertion and femoral tunnels were positioned anterior to both the AM and PL anatomic insertion.⁹⁹ Improper positioning of the bone tunnels has been identified as the most common cause of graft failure, and this has led many surgeons to adopt a more anatomic ACL reconstructive technique in which the graft replicates the original ligament as closely as possible.^{12,97}

Due to the anatomic double-bundle structure of the intact ACL, investigators have proposed a method of reconstruction which theoretically should duplicate the ligaments intended function.¹² The double-bundle reconstruction technique was designed as an effort to restore all mechanical aspects of ACL stability.¹⁰⁰ Although methods vary among surgeons, the proposed technique utilizes two separate grafts (and either one or two tunnels on both the tibia and femur depending on surgeon preference) to better replicate the anatomical anteromedial (AM) and posterolateral (PL) bundles of the native ACL.¹² Traditional single-bundle techniques were designed, primarily, to replace the anteromedial bundle. Results of this procedure have demonstrated adequate stability in the anteroposterior direction, however, issues with rotational control still remain.^{7,101} The addition of a second graft in the double-bundle technique was designed to address the issue of rotational laxity by aiming to restore the ACL's native two-bundle anatomy as closely as possible.⁹⁷ Several studies have commented on the success of this reconstructive method in restoring normal knee kinematics, however, there are some disadvantages.^{100,102,103} The major concern with double-bundle reconstruction is the difficulty in surgical technique.^{12,97} Inaccurate tunnel placement may lead to impingement and potentially graft failure. Additionally, due to its complexity, this method requires longer surgical time and makes revision surgery more challenging.¹²

In 2014, Björnsson et al. conducted an observational comparative study of 16,791

patients from the Swedish National Knee Ligament Register comparing revision rates between single-bundle and double-bundle ACL reconstruction. Over the seven-year observational period, 510/12,281 (2.1%) of single-bundle and 8/510 (1.6%) of double-bundle reconstructions were revised. Statistical analysis showed no significant difference in revision rate, KOOS scores or EQ-5D scores between the two surgical methods.¹⁰⁴ It is important to note that the study period represented a time of transition where many surgeons began adopting the newly introduced anatomic single-bundle and double-bundle techniques. The substantial learning curve in addition to complexity of the double-bundle technique may underestimate the true difference between these two surgical procedures.

A more recent systematic review of nine meta-analyses (ranging from 756 to 1,686 patients) by Mascarenhas et al. suggests that double-bundle ACL reconstruction provides better postoperative knee stability than a single-bundle graft. More specifically, seven of the nine studies found superior pivot shift results in the double-bundle ACL reconstruction when compared to single-bundle (two studies found no significant difference). Similarly, eight of the nine studies favored the double-bundle group in KT arthrometer scores when compared to the single-bundle group (one study found no significant difference between the two surgeries). An acknowledged limitation of this review is the heterogeneity among included studies in regards to combined analysis of anatomic and non-anatomic ACL reconstruction techniques. These variations may have yielded different stabilities, particularly rotational stability.¹⁰⁰

2.7.3 The Anterolateral Ligament (ALL)

Over the past decade, the ACL reconstructive technique has evolved in parallel with the increased understanding of insertional ligament anatomy. Despite the vast improvements in surgical outcomes, recent meta-analyses have shown that graft failure and anterolateral instability rates remain high among isolated ACL reconstructions. A recent focus on the peripheral structures contributing to knee stability has lead researchers to re-focus on the anterolateral ligament (ALL).¹⁰⁵ Originally identified by Segond in 1879, the ALL was described as a pearly, resistant, fibrous band inserting on the anterolateral aspect of the

proximal tibia.¹⁰⁶ It has since been referred to by many names, however, it was not until recently that the ALL was identified as a unique and individual structure with its own biomechanical contributions to knee stability.^{107,108}

In 2012, Monaco et al. investigated the kinematics of 10 fresh-frozen cadaver knees; (1) with the ACL intact; (2) after resection of the PL ACL bundle; (3) after resection of the AM ACL bundle; and (4) after cutting the ALL. Sequential resection of the ACL showed a significant increase in anteroposterior translation at 30 and 60 degrees of flexion ($p = 0.01$), but did not increase rotational laxity of the knee. However, after cutting the ALL, there was a significant increase in internal rotation at 30, 45 and 60 degrees of flexion ($p = 0.03$). The authors concluded that following sectioning of the ACL, resection of the ALL increased tibial rotation and this could be related to the anterolateral laxity of the ACL deficient knee and ultimately the pivot shift phenomenon.¹⁰⁹ Similar results were shown in a 2015 study by Pearsons et al., where 11 cadaveric knees were subjected to anterior drawer and internal rotation forces at various degrees of flexion. The authors concluded that the ALL is an important stabilizer of internal rotation at flexion angles >35 degrees.¹¹⁰

It has also been generally well documented that the Segond fracture (an avulsion fracture of the ALL at its insertion on the tibia) is pathognomonic of an ACL tear. Recognizing the biomechanical importance of the ALL, a number of authors have proposed the necessity of an extra-articular augmentation procedure to address the anterolateral instability of the ACL deficient knee.^{110,19}

2.7.4 The Extra-Articular Reconstruction

Early intra-articular ACL reconstructive techniques were considered by many to be complex and difficult to perform. Therefore surgeons were more than eager to adopt a simpler, less invasive technique that did not require open joint surgery.¹ The first documented extra-articular reconstruction was performed in 1907 by Fritz Lang who placed silk sutures across the joint space in an attempt treat knee instability.¹ Promising

results encouraged Martin Kirschner (1910) and Herman Matti (1918) to develop an extra-articular ACL substitution using a free fascial graft.^{111,112} With contributions from surgeons in the 1920's and 1930's the extra-articular reconstruction continued to evolve under the principle that "a torn ACL left little if any disability whilst the medial or tibial collateral ligament is of the utmost importance in the stability of the knee".¹¹³ It was not until 1937 that Frank Strickler pioneered the lateral extra-articular substitution which he combined with the intra-articular reconstruction.¹¹⁴ In his description of the combined intra/extra-articular reconstruction, Strickler used a long strip of fascia which he routed through the joint and across the antero-lateral capsule. The graft was fastened to itself at the entry point into the femur, forming a full loop which he believed could service both ACL and PCL insufficiencies.¹¹⁴

In 1972, Marcel Lemaire of Paris introduced a similar augmentation technique under the assumption that "the role of the ACL was to control external rotation." In his proposed technique, Lemaire tunneled the distally attached central fascia lata strip underneath the LCL, threaded it through a bony tunnel slightly posterior to the lateral femoral epicondyle and sutured it back against its origin at Gerdy's tubercle. By 1975, Lemaire had performed this technique on 328 isolated ACL ruptures and although he acknowledged that the procedure was ill equipped to control the anterior drawer, it did control some of the rotational instability associated with ACL deficiency. This appeared to be sufficient for patients returning to sporting activities and translated to good outcomes in 87% of those who underwent the procedure.¹¹⁵

In the mid-1970's, David MacIntosh devised a variation of the Lemaire technique called a 'lateral substitution reconstruction'. Avoiding the use of a bony tunnel, MacIntosh instead threaded the fascia through the lateral intermuscular septum before suturing the graft back onto Gerdy's tubercle.¹¹⁶ This procedure became popular among surgeons during the 1980's and 1990's and was used either in isolation or in combination with intra-articular reconstruction if significant laxity was present.^{116,117}

Over the last few years, journals have shown an increasing interest in combining ACL reconstruction with extra-articular augmentation.¹ Paper's by Zaffagnini et al. and

Marcacci et al. have shown support for this technique by demonstrating that the additional reconstruction not only protects the graft from excessive loads, but also improves lateral rotational control.^{21,22} The added anterolateral support appears even more desirable following recent evidence by Jonsson et al. who suggested that rotational instability may have a greater role than anteroposterior instability in the development of knee osteoarthritis. Sixty-three ACL reconstructed patients were assessed for ligament laxity (via both lachman and pivot shift tests) and knee joint degeneration (via bone scintigraphy and radiography) at two and five to nine year follow-up. Pivot shift results were graded as being either absent (negative) or present (positive), and anteroposterior laxity was defined as a side-to-side difference of 2.5 mm or greater. Results showed a greater scintigraphic activity of the subchondral bone in the lateral knee compartment among patients who had a positive pivot shift when compared to those who had a negative pivot shift ($p = 0.03$). However there was no difference in scintigraphic activity when comparing anteroposteriorly stable and unstable knees ($p = 0.2 - 1.0$). The increase in scintigraphic activity among rotationally unstable patients suggests that residual rotary mobility may be associated with an increased risk of post-operative osteoarthritis.¹¹⁸

A number of authors have published encouraging results in response to the extra-articular tenodesis combined with intra-articular ACL reconstruction. In 2006, Zaffagnini et al. conducted a prospective, randomized study comparing five-year clinical and radiographic outcomes of three commonly used ACL reconstruction techniques: (group I) bone-patellar tendon-bone autograft ($n=25$), (group II) four-strand hamstring autograft ($n=25$), and (group III) hamstring plus extra-articular plasty ($n=25$). Outcomes evaluated at follow-up included IKDC scores, Tegner scores, thigh circumference, anterior knee pain and kneeling pain, knee laxity (Pivot shift test, Lachman test and KT-2000 arthrometer test), range of motion, time to return to sport and radiographic evaluation. There were no significant pre-operative differences among the three groups regarding age, sex, time from injury to surgery or any of the aforementioned outcomes. At five-years follow-up, results showed a trend towards less pathologic laxity in group I and III compared to group II. The pivot shift test was positive in 12% of group I, 8% in group III and 36% in group II. Subjects showed a similar trend in Lachman scores where the incidence of positive findings (grade 1, 2 and 3) were highest in group II (28%), compared to group I

(8%) and group III (8%). Additionally, patients who received the hamstring tendon plus lateral plasty showed significantly better IKDC subjective scores and a faster return to sport than those who received a BPTB graft or four-strand HT graft. The superior scores demonstrated by group III lead authors to concluded that the use of a lateral plasty in combination with intra-articular reconstruction should be used in patients with an ACL deficient knee.²⁰

In 2015, Hewison et al. conducted a systematic review of the literature, looking at rotational laxity in patients who received a lateral extra-articular tenodesis in combination with an intra-articular ACL reconstruction. Outcomes of interest included the pivot shift test, IKDC scores and KT-1000/-2000 measurements. A search using nine databases yielded a total of 3,612 articles, of which 29 met the inclusion criteria (3,293 ACL alone; 1,245 ACL + extra-articular tenodesis). Of the eight randomized studies included, three concluded that there where no difference between groups with regards to overall outcome, while four studies favored the overall outcome of the extra-articular tenodesis and one favored the ACL reconstruction alone. A meta-analysis that included six RCTs and eight non-RCTs (ACL plus LET; n = 499, ACL alone; n = 642) reported that the odds of a positive pivot shift was twice as likely in the ACL alone group as to the ACL plus LET (OR=0.5; 95% CI, 0.3 to 0.8, p=0.002). However, there were no differences in IKDC scores (p = 0.75) or KT-1000/-2000 measurements (p = 0.84). These findings may reflect the fact that although some patients may objectively have residual rotational mobility, their current activity participation does not make demands on their knee such that the effects are limiting and would reflect in an IKDC. The authors also noted that several studies had an unclear to high risk of bias as a result of insufficient sample size, lack of internal validity and inconsistent methodology.²³

More recently, in May of this year, Song et al. published a similar systematic review of the role of the lateral extra-articular tenodesis plus ACL reconstruction in addressing high-grade pivot-shift. High grade pivot shift was defined as a moderate to severe rotational instability graded as 2 (clunk) or higher. Using the PubMed/Medline database, the authors identified 5 papers that met the eligibility criteria. Among these 5 comparative studies, the prevalence of a residual pivot shift following surgery was

significantly lower ($p < 0.05$) in patients who received the ACL plus LET (30/226, 13.3%) compared to those who received an ACL reconstruction alone (67/246, 27.2%). Similar to the findings by Hewison et al, Song did not find a significant difference in IKDC scores or anterior knee stability measures between the two treatment groups. The authors concluded that a combined ACL plus LET reconstruction was effective in eliminating the high-grade pivot shift phenomenon, however the review was based on low quality studies and there was a significant heterogeneity in surgical techniques among the included articles.²⁴

2.8 Biomechanical Assessment

Landing and/or cutting maneuvers have been acknowledged as the primary movements responsible for ACL injury.¹¹⁹⁻¹²¹ There is increasing evidence in the literature suggesting that neuromuscular deficiencies resulting in poor biomechanical control of the lower limb may predispose athletes to ACL injury during potentially hazardous sporting movements.¹²¹⁻¹²³ Due to the combined passive and dynamic stabilization provided by ligaments and muscles respectively, researchers have devised a number of laboratory-controlled ballistic tests to evaluate lower limb injury risk; the side-step cutting task, the drop landing and the drop vertical jump are the most documented methods of assessing movement mechanics.¹²⁴

2.8.1 The Drop Vertical Jump (DVJ)

Of the three aforementioned tasks, the drop vertical jump (DVJ) is the most commonly utilized biomechanical assessment of dynamic knee control.¹²⁴ Designed to replicate the physical demands of a land-and-go or rebound maneuver, commonly observed in basketball, the test requires patients to drop off a box, land with both feet onto the ground below and immediately rebound vertically into the air as high as they can.^{125,126} Although researchers have acknowledged the cost- and time-effective benefits of two-dimensional video analysis, three-dimensional marker-based motion capture is considered the ‘gold

standard' for joint kinetic and kinematic assessment of the DVJ in a clinical setting.^{127,128} The test itself has been shown to demonstrate a high within-session reliability with an intra-class correlation coefficient greater than 0.93.¹²⁶ Reliability of knee biomechanical values in the DVJ have also been evaluated by Ford et al. and Malfait et al. who showed that the majority of kinetic and kinematic variables have fair to excellent within-session (ICC, 0.67 to 0.99) and between-sessions (ICC, 0.59 to 0.92) reliability in a young, athletic female population.^{128,129} More recently, Gagnon et al. reported test-retest reliability for kinetic and kinematic variables during a DVJ in patients after ACL reconstruction. Frontal plane abduction moments and angles of 16 subjects were measured twice (one week apart) at 6 months following surgery. Results showed high intraclass correlation for knee abduction angle at initial contact (ICC, 0.81; 95% CI, 0.53 to 0.93), peak knee abduction angle at the deepest point of landing (ICC, 0.78; 95% CI, 0.47 to 0.92) and peak knee abduction moment (ICC, 0.90; 95% CI, 0.73 to 0.96), demonstrating that these DVJ variables continue to have excellent test-retest reliability in patients following ACL reconstruction.¹³⁰

2.8.2 Predicting ACL Injury

Many researchers have commented on the importance of neuromuscular control in knee stability, suggesting that any abnormalities may result in faulty movement patterns and ultimately an increased risk of injury. Current research focuses on four neuromuscular imbalances that the authors term ligament dominance, quadriceps dominance, trunk dominance and leg dominance.

When studying jumping mechanics, it is generally well understood that the dynamic stabilizers of the lower limb are responsible for the majority of force dissipation at impact.^{123,131,132} An insufficient muscular support has been previously described by Andrews and Axe as 'ligament dominance' whereby muscles of the lower extremity do not adequately absorb forces and therefore the passive structures, like the ligaments, must provide the necessary resistance,¹³³ which results in excessive loading through the ligaments of the knee, especially the ACL, which may lead to an increased likelihood of

injury.^{133,125} Some researchers have linked ligament dominance to high knee abduction moments coupled with internal rotation of the tibia, otherwise known as valgus collapse.^{125,134}

Quadriceps dominance is a gender biased neuromuscular imbalance more commonly seen in the female population who tend to land with less knee flexion than males.¹³⁵ It is characterized by a relatively high knee extensor to flexor recruitment (Q/H ratio), whereby the knee joint is primarily stabilized by the quadriceps muscles.^{135,136} A 1996 study by Hewett et al. compared the landing mechanics of 11 young female volleyball players to 9 male controls matched by age, height and weight. Results showed that males demonstrated knee extensor moments (reflective of net hamstring muscle activity) that were threefold higher than females when decelerating from a landing (9.9 Nm versus 3.3 Nm, %BW×ht).¹³⁶ The study also showed significantly increased knee abduction (valgus) moments among the female group suggesting that quad dominance may be associated with the high risk landing pattern.¹³⁶ After the implementation of a neuromuscular training intervention to correct the Q/H ratio, females demonstrated significantly lower knee valgus moments and peak impact forces.¹³⁶ Authors were able to conclude that adequate co-contraction of the knee extensors and flexors may help balance compression at the knee joint and reduce knee abduction torques and valgus collapse.¹³⁶

Trunk dominance has been simply defined as inadequate control of trunk movement in three-dimensional space.¹³⁷ An inability to correctly sense position of the trunk leads to greater movement following a perturbation, which has been linked to greater risk of future ACL injury.^{138,139} In 2009, Hewett and Torg conducted a video analysis of lateral trunk and knee motion during non-contact ACL injury. Still captures of 17 young athletes at time of injury (10 females and 7 injured males) and 6 uninjured female controls, were used to measure trunk and knee angles. Results showed a higher lateral trunk angle among female athletes at time of injury than their male counterpart ($p \leq 0.05$) and a trend towards greater lateral trunk angle when compared to uninjured females during a similar movement task ($p = 0.16$). Similar differences were demonstrated when comparing knee abduction angles among the three groups. Female ACL-injured athletes demonstrated a significantly higher knee abduction angle at time of injury when compared to their male-

injured counterpart ($p \leq 0.05$), and showed a trend towards greater abduction angles when compared to uninjured female controls, although differences were not significant ($p = 0.13$). Findings of this study suggest that lateral sway may be an underlying contributor of the abduction mechanism of ACL injury. Although the phenomenon has been demonstrated by both sexes, only female athletes have been documented of having significant trunk proprioceptive deficits which may predispose them to ACL injury.^{138,140}

In 2007, Zazulak et al. conducted a prospective biomechanical-epidemiological study looking at core proprioception and its role in knee stability. At the start of the study, 277 Yale varsity students participated in a core proprioception experiment (described and validated by Taimela et al)¹⁴¹. During the three-year follow-up, 25 athletes sustained a knee injury (any combination of ACL, MCL, patellofemoral, or meniscus). Out of all trunk movements, lateral trunk displacement was the strongest predictor of ligament injury ($p = < 0.01$).¹⁴⁰ Active proprioceptive repositioning was able to predict knee ligament/meniscus injury with 86% sensitivity and 61% specificity in female athletes, although, the low event rate for specific ligament injuries, may preclude the ability of active proprioceptive repositioning to predict ACL injury.¹³⁸

The leg dominance imbalance theory suggests that side-to-side imbalances in strength, neuromuscular coordination and flexibility can be important predictors of increased injury risk.¹³⁷ In 1991, Knapik et al. conducted a pre-season strength and flexibility assessment on a group of 138 female collegiate athletes. During the three-year follow-up period, 32% of the pre-screened athletes went on to suffer a lower extremity injury. In comparing initial strength differences at baseline, results showed that there was a trend for higher injury rates associated with knee flexor or hip extensor differences $>15\%$ between both limbs.¹⁴²

In 2005, Hewett and colleagues conducted a prospective cohort study with the hypothesis that pre-injury biomechanical measures could be used to predict ACL injury risk. Before the start of their sport season, 205 high school female athletes were screened via three-dimensional biomechanical DVJ analysis. At the end of the year, nine participants sustained an ACL injury during play. Initial screening biomechanical values were

compared between the injured and uninjured athletes and results showed that those who were injured had a 2.5 times greater knee abduction moment (95% CI, 1.4 to 3.6, $p < 0.001$) and 20% higher ground reaction force (95% CI, 1.1 to 1.3 $p < 0.05$) compared to those who remained uninjured. Additionally, side-to-side knee abduction moment differences were 6.4 times greater in ACL-injured versus the uninjured females (95% CI, 3.9 to 33.2, $p < 0.001$). Stance time was also 16% shorter among injured patients; hence, they experienced these increased forces, and moments over briefer periods, resulting in higher impulse forces. Knee abduction moments (KAM) (which directly contribute to lower extremity dynamic valgus) showed a sensitivity of 78% and a specificity of 73% for predicting ACL injury events. The authors concluded that KAM could be used as a key predictor of potential ACL injury risk in a group of young female athletes.¹²³

2.8.3 Landing Mechanics following ACL Reconstruction

In addition to identifying individuals at risk of sustaining an initial ACL injury, tests such as the DVJ can also be used to assess overall function following surgery. ACL reconstruction improves the mechanical stability of the knee; however, appropriate training and rehabilitation are recommended to improve the chances of full recovery. Athletes who have undergone ACL reconstruction demonstrate altered lower limb biomechanics compared to healthy individuals.^{10,11} These alterations are thought to be important since individuals with prior ACL injury are at a 5-15 times increased risk of subsequent ACL tear.¹⁴³ Therefore, it is important to determine whether a fully rehabilitated ACL reconstructed knee functions similar to one without injury, or whether the individual demonstrates neuromuscular imbalances that predispose them to re-injury.

In 2001, Decker et al. conducted a study to determine whether fully rehabilitated ACL reconstructed athletes demonstrate neuromuscular imbalances during a high demand functional task. Kinetic and kinematic performance during a 60-centimeter vertical drop landing was assessed in 22 patients (11 ACL reconstructed recreational athletes and 11 age, gender and sport matched healthy controls). All subjects in the ACL reconstruction group (ACLR) received a hamstring tendon autograft within 3 months of injury and

completed the jumping test at a time point greater than one year following surgery. Hip, knee, and ankle muscle power values were calculated as the product of the joint angular velocities and moments. Results showed that athletes who received an ACL reconstruction had a reduced contribution of energy absorption from the hip extensors (healthy, 32%; ACLr, 20%) and increased contribution from the ankle plantar flexors (healthy, 28%; ACLr, 39%). There were no differences in ground reaction force between the two groups; however, ACLr subjects took longer to reach max values. The authors suggest that these differences may be reflective of a protective mechanism which limits the muscular output of the hip extensors, including the hamstrings and compensates using ankle plantarflexors.¹⁴⁴

In 2007, Paterno et al. conducted a similar study comparing DVJ landing mechanics between 14 ACL reconstructed female athletes at 27.4 ± 13.8 months post-surgery (ACL group) and 18 healthy controls. The primary outcome was vertical ground reaction force (VGRF). Unlike the findings by Decker et al, Paterno and colleagues found that athletes in the ACL reconstruction group demonstrated increased VGRF ($p = 0.001$) and loading rate ($p = 0.001$) on the uninjured limb during landing when compared with their injured limb and both limbs of the control group. The reconstructed limb of the ACL group also showed significantly weaker force production ($p = 0.03$) at takeoff than the uninvolved limb and both limbs of the control group.¹⁴⁵

Giampietro et al. recently published an in-depth retrospective analysis of landing mechanics following ipsilateral semitendinosus and gracilis autograft (ISGA) ACL reconstruction. Fourteen patients in the ISGA ACL reconstruction group (21.4 ± 10.7 months post-surgery) and 14 matched, healthy controls underwent isokinetic strength testing and single-leg vertical drop landing (VDL) kinetic, kinematic and surface electromyography (EMG) assessment. Results showed no significant difference in hamstring muscular strength and endurance; however, there were significant differences in preparatory and reactive muscle activation at landing. Similar to the results by Paterno et al. ISGA ACL reconstructed patients demonstrated significantly decreased peak VGRF upon landing on the involved lower extremity compared to the uninvolved limb ($p = 0.028$) and matched control limbs ($p = 0.0001$). Athletes in the ISGA ACL reconstruction

group also displayed significantly greater peak hip joint flexion angle ($p = 0.03$), knee joint flexion angle ($p < 0.01$) and ankle flexion angle ($p = 0.02$) at maximum (peak) VGRF when landing on the involved lower extremity compared to the matched control. Increased flexion angles at the hip, knee and ankle with a decreased VGRF suggests that ACL reconstructed patients adapt a lower impulse landing mechanism in an effort to dissipate forces through the knee.¹⁴⁶

In 2010, Paterno et al. conducted another study on ACL reconstructed patients with the hypothesis that neuromuscular control and postural stability could be used to predict the relative risk of a second ACL injury.¹¹ Fifty-six athletes (age, 16.41 ± 2.97) underwent a prospective biomechanical screening of a DVJ after ACL reconstruction. Testing was administered before return to pivoting sport and subjects were followed for 12 months for occurrence of a second ACL injury. Thirteen athletes suffered a second ACL injury at the end of the one year follow-up. Using kinetic and kinematic differences between re-injured and uninjured individuals, the authors were able to identify predictors of second ACL tear. Sagittal plane knee moments and frontal plane knee kinematics during landing, transverse plane hip kinetics, and deficits in postural stability predicted second injury in this population with a sensitivity of 0.92 and specificity of 0.88.

Similar to Giampietro et al. (2008), Delahaunt and colleagues also conducted a study in 2011 to identify lower limb kinematic alterations during a DVJ following ACL reconstruction, although his study population consisted only of females.¹⁴⁷ Fourteen ACL reconstructed patients (mean time of 4.4 years since surgery) and 14 non-injured controls performed three DVJ's. When compared to the controls, the ACL reconstructed group displayed an increased peak and time-averaged hip adduction ($p < 0.05$) and hip internal rotation ($p < 0.05$) following landing. The ACL reconstruction group also showed a decrease in knee adduction ($p < 0.05$) and flexion ($p < 0.05$) following landing. These findings are consistent with the results from pre-ACL injury prediction studies, suggesting that ACL reconstructed female athletes still exhibit altered lower limb kinematic profiles during sport specific landing tasks.

Ortiz et al. published similar results in a 2014 cross-sectional biomechanics study.¹⁴⁸

Fourteen post-ACL reconstructed patients, with a semitendinosus-gracilis autograft, and 16 non-injured women performed a series of single- and double-legged drop jumps. Results showed a trend towards greater dynamic knee valgus in the ACL reconstructed group, although findings were not significant. An acknowledged limitation was that small sample size did not allow for adequate power.

In early 2014, Goerger et al. used pre-injury baseline biomechanical data from the Joint Undertaking to Monitor and Prevent ACL (JUMP-ACL) study to assess the changes in double-leg jump landing mechanics following ACL injury and reconstruction.¹⁰ Of the patients assessed at baseline, 31 went on to sustain an ACL-injury. All 31 patients and 39 uninjured, matched controls completed a repeated, follow-up biomechanics assessment before surgery and prior to return to sport. Since baseline JUMP-ACL data was collected for the dominant limb only, all ACL-reconstructed subjects were subdivided into two group depending on which limb was injured: ACLR-injured leg group (n = 12) and ACLR-uninjured leg group (n = 19). Altered lower-limb biomechanics were shown following injury and after surgery. Both ACL reconstruction groups demonstrated an increase in frontal plane movements at landing (increased hip adduction, and increased knee valgus). The ACL-injured leg group also demonstrated a decrease in sagittal plane loading (decreased knee extension moment and hip flexion moment and decreased anterior tibial shear force) after injury and following surgery when compared to the ACL-uninjured leg group. No high-risk biomechanical changes were observed in the control group. Authors concluded that ACL injury and subsequent reconstruction caused an alteration in movement patterns of both the injured and uninjured limb. These findings suggest that the detrimental biomechanical changes brought on by ACL injury are not ameliorated upon reconstruction and traditional therapy. Athletes continue to demonstrate high-risk movement patterns that are predictive of future ACL injury.

KAM has also been shown to be sufficiently sensitive to detect differences between groups who underwent ACL reconstruction using different graft types. Specifically, Papalia et al. published results for a randomized trial comparing the landing biomechanics of 40 ACL reconstructed female athletes who received either a hamstring tendon graft (n = 20) or a patellar tendon graft (n = 20). Two weeks after the conclusion

of a 24-week custom rehabilitation program (focusing on muscle strength recovery, proprioception and joint stabilization), all patients performed a single-leg hop, a crossover triple hop, a timed hop and KAM test (similar to the DVJ). While there was no significant difference in the single-leg hop, crossover triple hop and timed hop tests between the two treatment groups, those who received a patellar tendon graft demonstrated a significantly lower knee abduction moment during the KAM test, than those who received a hamstring tendon graft ($p < 0.0001$). These findings present the notion that graft type may affect the KAM value and, subsequently, dynamic knee stability. Functional jumping scores were then compared to a historical control group of 40 athletes, who underwent the same reconstructive procedures but used a traditional rehabilitation protocol. Results showed a statistically significant difference in favor of the custom rehabilitation program for all four functional tasks ($p < 0.0001$), suggesting that full recovery of knee stability depends not only on surgical reconstruction, but on the type of rehabilitation as well.¹⁴⁹

Clarke et al. (2014) investigated the long term adaptations in lower limb biomechanics during sport-specific movement patterns following ACL reconstruction. Thirty-six patients (18 ACL reconstructed and 18 controls) performed a maximal drop-jump land and an unanticipated cutting task at >2 years post-injury. Three-dimensional kinetics and kinematics of the hip and knee were measured at touchdown (TD, first 40 milliseconds after landing) and throughout the entire landing stance phase. During the maximal drop-jump task, ACL reconstructed patients demonstrated a significantly higher maximum hip flexion ($p = 0.003$) and external-internal knee rotation range of motion at TD ($p = 0.035$) compared to the control group. Additionally, the ACL reconstruction group showed higher maximum hip flexion ($p = 0.002$), hip abduction-adduction range of motion ($p = 0.015$) and external-internal knee rotation range of motion ($p = 0.027$) than the control group during the entire landing stance phase. There were no significant differences in landing biomechanics between injured and uninjured limbs of the ACL reconstructed patients.¹⁵⁰ The frontal and transverse plane knee ROM differences, presented between the ACL-reconstructed and control subjects, support previous investigations which label these variables as risk factors for re-injury.^{11,151} High internal-external rotation range of motion values among the ACL reconstructed group are also consistent with evidence

from cadaveric studies^{48,107}, confirming that traditional reconstructive techniques do not adequately control rotational stability around the knee joint.

In 2015, Setuain et al. conducted a cross-sectional study evaluating unilateral and bilateral jump performance among 22 male (6 ACL-reconstructed and 16 uninjured) and 21 female (6 ACL-reconstructed and 15 uninjured) elite handball players who were fully rehabilitated (6.2 ± 3.4 years) after ACL reconstruction. Results showed that previously ACL-reconstructed female athletes had a lower bilateral contact time (0.43 ± 0.18 vs. 0.35 ± 0.15 seconds, $p < 0.05$) on their reconstructed limb compared with the dominant legs of the uninjured control athletes.¹⁵² These findings are consistent with the conclusions by Hewett et al. (2005) who associate shorter landing times with more abrupt impulses through the knee joint and consequently an increased risk of injury.¹²³

Most recently, in late 2015, Schmitt et al. evaluated the effects of quadriceps muscle group symmetry between legs on lower limb landing mechanics following ACL reconstruction. One hundred and twenty-four patients (77 ACL reconstructed, 47 uninjured controls) were divided into strength groups based on quadriceps index score ($QI = [\text{involved limb strength} / \text{uninvolved limb strength}] \times 100\%$): high quadriceps group (HQ, $QI \geq 90\%$) and low quadriceps group (LQ, $QI \leq 85\%$). Overall results found that the LQ group demonstrated greater asymmetry in all kinetic and ground reaction force variables compared to the HQ and control groups. More specifically, pairwise comparisons demonstrated that patients in the LQ group had greater asymmetry in peak vertical ground reaction force, peak loading rates and peak external knee flexion moments than the HQ group ($p < 0.001$, $p = 0.009$ and $p \leq 0.001$, respectively) and the control group ($p < 0.001$, $p = 0.043$ and $p \leq 0.001$, respectively). However, there were no differences in limb symmetry measures between the HQ and control groups ($p > 0.05$). The authors concluded that isometric quadriceps femoris strength deficits $>15\%$ negatively affect knee joint loading mechanics during a bilateral landing task. Conversely, ACL reconstructed patients with nearly symmetrical quadriceps femoris strength ($QI \geq 90\%$) demonstrate landing patterns similar to uninjured individuals.¹⁵³

2.9 Summary

Biomechanical assessments of patients who have undergone an ACL reconstruction have shown that conventional surgical techniques are unable to restore normal tibial rotation when compared to the contralateral knee. Additionally, researchers have identified a number of neuromuscular imbalances that manifest after ACL injury and reconstruction. Evaluating the kinetics and kinematics of a functional task like the drop vertical jump, researchers have identified individuals who may be at a high risk of re-tear.

Some studies have linked biomechanical imbalances to anterolateral capsular injury, suggesting that augmentation of the ACL reconstruction with an extra-articular graft may provide improved knee stability in patients at high risk of graft failure. Among the surgical techniques documented, the LET has reported excellent clinical results; however, its ability to control dynamic knee stability during a functional task has yet to be assessed.

Chapter 3

3 Objectives

The primary objective of this study was to compare the landing mechanics of a drop vertical jump (DVJ) between patients receiving anterior cruciate ligament (ACL) reconstruction with lateral extra-articular tenodesis (LET) versus anterior cruciate ligament reconstruction alone. The primary outcome was peak knee abduction moment (KAM) generated during the landing phase of the jump. We hypothesized that there would be a difference in peak KAM between patients undergoing ACL reconstruction alone and patients undergoing ACL reconstruction with an LET at six and twelve months following surgery. Secondary jump biomechanics outcomes included knee abduction angle, internal rotation angle and moment, knee flexion angle and moment, and vertical ground reaction force

The secondary objective of this study was to determine whether patient reported fear associated with physical activity (FABQ-PA score) was different between those who could and could not perform DVJs at six months following surgery. A registered kinesiologist permitted patients to perform drop jumps upon successful completion and safe execution of a hop test. We hypothesized that patients who could perform the DVJ test at six months would achieve a lower score on the FABQ-PA than patients who could not perform the jumps.

Chapter 4

4 Methodology

We recruited patients consecutively from an ongoing randomized trial (NCT02018354) led by the Fowler Kennedy Sport Medicine Clinic. This sub-study only involved patients from our centre and began on June 8, 2015 following institutional approval by the Health Sciences Research Ethics Board (HSREB) at Western University (Appendix A).

4.1 Eligibility

Eligibility was determined during an initial consultation by one of the three orthopaedic surgeons involved the study. All patients presenting with an ACL deficient knee were screened and asked if they would like to participate in the study. We then presented patients with the Letter of Information (Appendix B) and interested patients were assessed for eligibility. To be eligible for participation, patients had to be between the ages of 15 and 25 years, and willing to undergo ACL reconstructive surgery for an unstable ACL deficient knee where instability was defined as having two or more of the following, (1) a grade two pivot shift or higher; (2) participation in a pivoting sport at a competitive level; and (3) generalized ligamentous laxity (determined by a Beighton score of four or higher) or genu recurvatum more than 10 degrees.

We excluded patients from the study if they (1) had previously undergone ACL reconstruction on either knee; (2) had bilateral ACL insufficiency; (3) had an asymmetric varus knee alignment greater than three degrees; (4) presented with a multiligament injury where two or more ligaments required surgical repair or reconstruction; (5) had a articular cartilage defect that required treatment other than debridement (identified during arthroscopy); (6) were unable to speak, understand, or read English; (7) had a psychiatric illness or cognitive impairment that precluded informed consent; (8) were unwilling to participate.

4.2 Randomization

Patients were randomized at the time of surgery by either the nursing staff or research student following confirmation of eligibility by the surgeon using arthroscopic diagnosis of the knee joint. Once confirmed, patients were randomized on a 1:1 basis to receive either (1) ACL reconstruction alone (control group); (2) or ACL reconstruction with lateral extra-articular tenodesis (LET) (experimental group). Randomization was stratified by gender, surgeon and meniscal repair (requiring a change in post-operative rehabilitation) in permuted block sizes of two and four.

4.3 Interventions

4.3.1 Control: Anterior Cruciate Ligament Reconstruction

All patients in the control group underwent an anatomic ACL reconstruction alone, using an autologous hamstring graft. Semitendinosus was tripled or quadrupled if the graft diameter was found to be less than 8mm. Femoral tunnels were drilled using an anteromedial portal technique and femoral fixation was achieved using an Endobutton. An interference screw was used to provide tibial fixation.

4.3.2 Experimental: Anterior Cruciate Ligament Reconstruction with Lateral Extra-Articular Tenodesis

All patients randomized into the experimental group received the same anatomic ACL reconstruction as the control group. In addition to this procedure, they also received an LET on the anterolateral aspect of their knee. This additional procedure required an oblique skin incision spanning from the lateral epicondyle to Gerdy's tubercle (measuring approximately five-centimeters in length). Leaving the distal attachment on Gerdy's tubercle intact, a one-centimeter wide by eight-centimeter long strip of iliotibial (IT) band was released and a #1. vicryl whip suture was applied to the free end, leaving the needle attached. The surgeon then tunneled the graft under the fibular collateral ligament (FCL)

and attached it to the femur just distal to the intermuscular septum and proximal to the femoral insertion of the FCL using a Richard's staple (Smith and Nephew). Fixation was performed at neutral tibial rotation with the knee flexed at 90 degrees. The free end of the graft was then looped back onto itself and sutured with minimal tension applied to the graft.

All patients, regardless of group allocation underwent identical postoperative rehabilitation, following a protocol created by the physical therapy department at the Fowler Kennedy Sport Medicine Clinic (Appendix C).

4.4 Testing Protocol

DVJ testing was done in the Wolf Orthopedic Biomechanics Laboratory (WOBL) within the Fowler Kennedy Sport Medicine Clinic.

All testing took place during the mandatory postoperative visits with the orthopedic surgeon who performed the operation. Upon approval from the surgeon, patients underwent a hop test (as part of the STABILITY study protocol) administered by one of two registered kinesiologists, both of whom were blinded to treatment group. The assessment required patients to perform a series of single-leg hops including: (1) a single hop for distance; (2) a timed six-meter hop; (3) a triple hop for distance; (4) and a crossover hop for distance. Both kinesiologists were trained to identify unsafe movement patterns that put the patient at risk of re-injury. Some of these patterns included stiffness; identified as an abrupt landing with minimal knee flexion, valgus collapse; where the patients' knee collapses medially during landing, instability; or a general lack of control when performing the hops and apprehension; where the patient verbally addresses their fear associated with the movement and refuses to jump to their fullest potential. Patients whose movements were deemed unsafe were not permitted to perform the DVJ's.

4.4.1 The Drop Vertical Jump (DVJ)

The drop vertical jump (DVJ) is a functional test used to examine the landing mechanics of a movement that mimics the physical demands of a competitive jumping sport like basketball or volleyball.^{154,155} Used in conjunction with three dimensional motion capture software the DVJ has been used as a screening tool to identify movement patterns that put individuals at risk of ACL injury.^{154,156,10} The test is particularly suitable for patients who are preparing for return to sport because it allows for a pragmatic evaluation of knee stability during sport specific movements.

4.4.2 Data Collection

Data was collected using an 11-camera three-dimensional motion analysis system (Cortex 5, Motion Analysis Corporation, Santa Rosa, CA, USA) and three floor-mounted force plates (Advanced Mechanical Technology, Watertown, MA, USA). The research student performed calibration on each day of testing to ensure that all cameras were synchronized to each other as well as the force plates embedded in the floor.

All patients were fitted with a modified Helen Hayes passive reflective marker set with four additional markers placed on the right scapula, the spinous process of the tenth thoracic vertebra and both greater trochanters. Another four markers, placed on both medial knee joint lines and both medial malleoli, were used during three static recordings to determine virtual joint center positions, and were removed prior to jump testing.

Two static trials (three seconds each) were recorded with the patient standing motionless in the middle of one force plate. A third static trial was recorded with the patient standing on a 31-centimeter box from which DVJ's would be completed. All patients were given the same set of instructions and became familiarized with the testing procedure by performing one practice jump. All jumps were performed in the presence of two research students who were blinded to group allocation via a Tubigrip sleeve worn over the operative limb since incisional scars were unique to procedure. One student recorded data (on data collection form, Appendix D) while the other explained the testing protocol to

the participant and ensured that jumps were correctly executed. We asked patients to stand on the box positioned directly behind two force plates embedded in the floor. We then instructed them to drop off the box, land on the force plates with both feet, and immediately rebound vertically into the air as high as able (Figure 1). A total of five jumps were recorded with kinematic and kinetic data collected at 120 Hz and 1200 Hz respectively. Trials were repeated if patients lead with one limb during the initial drop, or if their feet landed off the force plate on either rebound or landing.



Figure 1: Sequence progression of the drop vertical jump. A, subject's starting position. B, drop off the 31 cm-height box. C, mid-stance phase of the initial landing. D, rebound

4.4.3 Post Processing

Once testing was complete, the research student tracked all static trials and three out of the five DVJ trials. The three initial static trials were used to determine relative marker orientation, body mass, and virtual joint centers for the hip, knee and ankle joints. The offsets from the real markers that remained on the person during the dynamic jump trials were calculated from the static recordings using custom post-processing software. We

then used the Skeleton Builder engine within Cortex to create body segments (bones, calculated from one marker center to another) and the Mass Model Editor (Kin Tools RT package) to scale specific body segment masses to individual height, weight and gender (Figure 2.B). After the skeleton model was defined and mass model information was entered, variables of interest were calculated and depicted using presentation graphs within Cortex. Kinetic and kinematic graph data was then exported and processed using a Butterworth filter with an input frequency of 12 Hz while force plate data was filtered at 100 Hz.

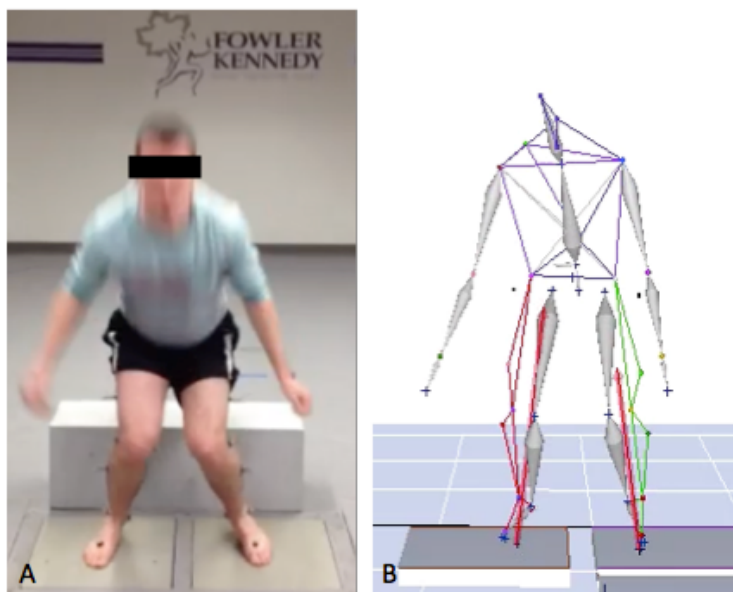


Figure 2: A, still capture of a patient performing the drop vertical jump (mid-stance phase). B, screenshot of the same patient as it is seen in Cortex after post processing.

4.5 Outcome Measures

We measured outcomes at 6 and 12 months following surgery. For the purposes of this thesis, we have reported results from the 6 month follow-up only.

A vertical ground reaction force (VGRF) of 10 N to identify the point of initial contact (IC) with the ground, as well as the toe-off (TO) prior to the maximal jump. We reported kinematic variables of interest as the maximum (peak) values during IC and stance phase (IC to TO). Moments and ground reaction forces were reported for stance phase only. All moments and angles were plotted against 100% of the stance phase and peak values for each subject were expressed as the mean of three trials.

4.5.1 Primary Outcome Measure

The primary outcome was peak knee abduction moment (KAM) produced during the entire stance phase of the DVJ. We used inverse dynamics to calculate moments at the knee joint center between the shank segment (extending from the virtual knee joint centre to the virtual ankle joint center) and its parent thigh segment (extending from the virtual hip joint center to the virtual knee joint centre). The KAM was normalized to body weight and height (%BW×ht).

4.5.2 Secondary Outcome Measures

The secondary outcome measures were knee abduction angle, internal rotation angle and moment, knee flexion angle and moment, vertical ground reaction force and a fear avoidance beliefs questionnaire – physical activity subscale (FABQ-PA).

4.5.2.1 Kinetic and Kinematic Outcomes

Kinematic variables of interest included; peak knee abduction angle (KAA); peak knee flexion angle (KFA); and peak knee rotation angle (KRA). Kinetic variables of interest included; peak vertical ground reaction force (normalized to BW); peak knee flexion moment (KFM); and peak knee rotation moment (KRM). All kinematic variables were extracted as the maximum value produced during the IC and stance phase of the DVJ. Like the peak KAM, all kinetic variables were normalized to body weight and height and calculated using inverse dynamics. Moments and forces were reported during stance phase only.

We chose our primary outcome based on previous studies comparing ACL reconstruction to healthy controls.^{157,123} Several authors have suggested that athletes with high knee abduction loads are at an increased risk of ACL injury.^{157,123,158} More specifically, a recent paper by Myer et al. associated KAMs >25.3 Nm with a 6.8% risk of subsequent ACL injury compared to a 0.4% risk if below this value.¹⁵⁹ Although this threshold is based on nine ACL tear events out of 205 screened female athletes, it provides researchers with a surrogate outcome against which ACL injury risk may be predicted. To our knowledge, there has been no prior research conducted on the landing mechanics of patients with the LET, therefore we selected additional kinetic and kinematic variables that would give us a comprehensive evaluation of knee stability in three dimensions.

4.5.2.2 Fear Avoidance Beliefs Questionnaire – Physical Activity Subsection

The FABQ is a patient reported questionnaire that was originally developed to investigate fear avoidance beliefs among patients with low back pain.¹⁶⁰ The full evaluation consists of two subsections, a physical activity subscale (with 5 items) and a work subscale (with 11 items). Because the work subscale is generally not applicable to our patient population, we only administered the physical activity component of this questionnaire.

In recent years, the FABQ has been used to assess fear avoidance beliefs in people with knee pathology and has shown adequate internal consistency and test-retest reliability.^{161–163} Like Ross MD we modified the FABQ-PA for our study by replacing the word “back” with “knee” and changing descriptors of physical activity from “bending, lifting and driving” to “walking, running and kneeling” (Appendix E).¹⁶³ The FABQ-PA subsection on its own has proven to be a reliable assessment tool in populations who have undergone ACL reconstruction with an intraclass correlation coefficient (ICC) of 0.92.¹⁶³

Patients completed the questionnaire immediately prior to DVJ testing at 6, 12 and 24 months following surgery. All five statements were numerically graded on a scale of zero to six, with higher scores indicating greater fear associated with physical activity. Total scores were then calculated by adding individual item values for questions one through five, to get a total score with a maximum of 30 points.

4.6 Sample Size

Sample size was calculated *a priori* using a two-sided alpha of 0.05. Statistical power was set at 0.80 to detect a moderate effect size of 0.50. It was determined that a sample size of 64 patients would be required per group. Based on the loss to follow-up in the STABILITY study throughout the first year, we anticipating a drop-out rate of 10%. Therefore the sample size was increased to 70 patients per group, for a total of 140 patients.

4.7 Statistical Analysis

We used SPSS Statistics Version 24.0 (IBM Corp., Armonk, NY) to perform all statistical tests. We used means and standard deviations to summarize continuous variables (height, weight, age, time from injury to surgery) and proportions for categorical variables (sex, operative limb, limb dominance and mechanism of injury).

We used independent groups t-tests to assess differences in kinetic and kinematic

variables between patients undergoing ACL reconstruction versus patients undergoing ACL reconstruction with an LET. We present means, standard deviations, mean differences and 95% confidence intervals for both groups. All tests were two-sided with $p \leq 0.05$ being significant. The independent groups t-test was used to examine difference in FABQ-PA scoring tendencies between those who were and were not able to perform jumps at six months following surgery.

Chapter 5

5 Results

5.1 Participant Flow

We screened 91 consecutive patients currently participating in an ongoing randomized trial (NCT02018354) led by the Fowler Kennedy Sport Medicine Clinic, London, Ontario, Canada. Of these 91 patients, 7 declined participation and one was ineligible because their BMI (36.2 kg/m^2) exceeded what the kinesiologist considered a safe threshold for performing the test. At the time of this thesis, 48 patients were included in our analysis (24 ACL alone and 23 ACL plus LET)(Figure 3).

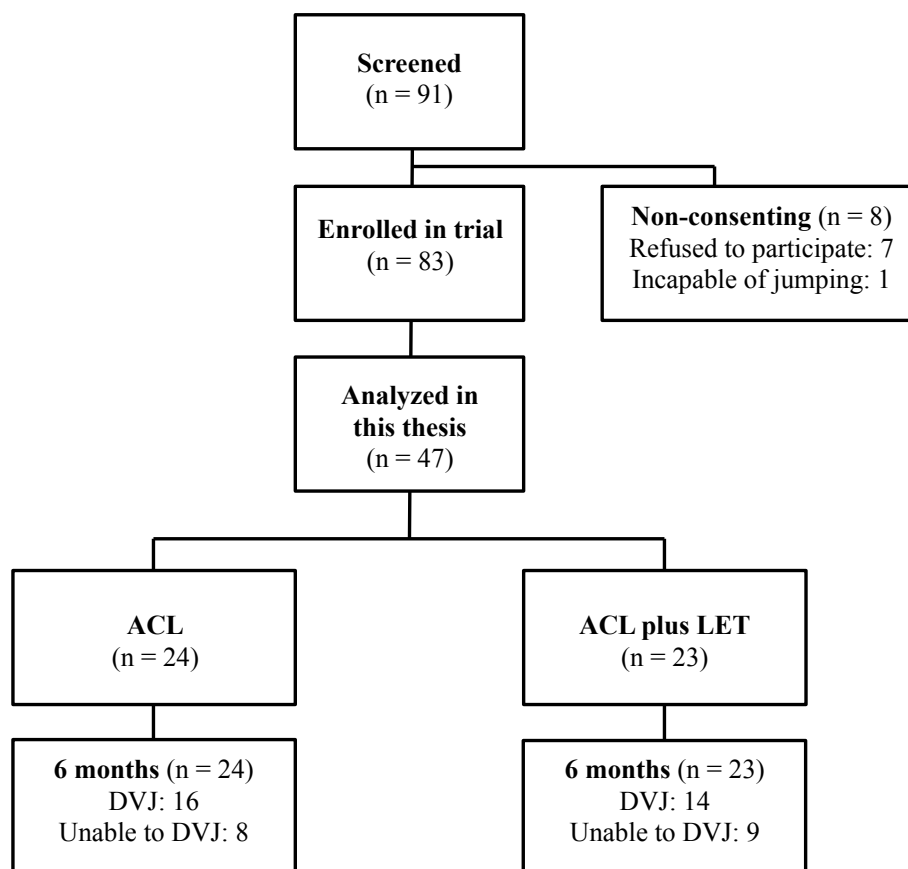


Figure 3: Participant flow through the study

5.2 Ability to Complete Testing

The patients within each treatment group were categorized as either Jumpers or Non-jumpers, depending on whether they were able to complete the hop test. Of the 48 patients included in our analysis, 8 (33%) patients in the ACL group and 9 (39%) patients in the ACL plus LET group were unable to finish the hop test (Relative Risk, 1.17; 95% CI, 0.5 to 2.5)(Risk Difference, 0.06; 95% CI, -0.2 to 0.3).

5.2.1 Jumpers

At the time of analysis, 30 patients had completed six month postoperative DVJ testing. All patient demographics were similar between the two treatment groups (Table 1).

Table 1: Baseline demographics for anterior cruciate ligament (ACL) reconstructed patients with and without a lateral extra-articular tenodesis (LET), who performed the drop vertical jump (DVJ) six months following surgery.

Demographic Characteristics	Group 1: ACL (n = 16)	Group 2: ACL plus LET (n = 14)
Sex, n (%) Male	7 (44)	7 (50)
Mean Age \pm SD (yrs)	19.3 \pm 3.0	19.4 \pm 3.5
Mean Height \pm SD (cm)	173.0 \pm 10.0	170.6 \pm 9.4
Mean Weight \pm SD (kg)	78.1 \pm 17.2	68.7 \pm 16.6
BMI \pm SD (kg/m ²)	25.9 \pm 6.2	23.1 \pm 3.4
Median time from injury to surgery (min to max) (mos)	4.2 (0.7 to 20.2)	4.3 (0.85 to 118.7)
Operative Limb, n (%) Dominant	8 (50)	6 (43)
Mechanism of Injury, n (%) Contact Non-contact	3 (19) 13 (81)	3 (21) 11 (79)

Injury during sport participation, n (%)	16 (100)	14 (100)
Soccer	5 (31)	4 (29)
Basketball	2 (13)	0 (0)
Football	0 (0)	6 (42)
Other	9 (56)	4 (29)

Abbreviations: SD = standard deviation, min = minimum, max = maximum

5.2.2 Non-Jumpers

At six months following surgery, eight patients (three male) in the ACL group and nine patients (one male) in the ACL plus LET group were unable to complete the DVJ test. One patient experienced a graft failure between three and six months postoperative and was therefore unable to perform the hop test or the DVJ test. The other 16 patients attempted the hop test, but were unable to finish because of apprehension (n= 7), stiffness (n= 6), valgus collapse (n= 5) or instability (n= 3). They were therefore not permitted to perform the DVJ test (Table 2).

Table 2: Baseline demographics for anterior cruciate ligament (ACL) reconstructed patients with and without a lateral extra-articular tenodesis (LET), who could not perform the drop vertical jump (DVJ) six months following surgery.

Demographic Characteristics	Group 1: ACL (n = 8)	Group 2: ACL plus LET (n = 9)
Sex, n (%)		
Male	3 (38)	1 (11)
Mean Age \pm SD (yrs)	21.6 \pm 0.9	19.3 \pm 0.9
Mean Height \pm SD (cm)	170.4 \pm 8.4	172.1 \pm 5.7
Mean Weight \pm SD (kg)	66.4 \pm 12.5	74.5 \pm 13.8
Operative Limb, n (%)		
Dominant	6 (75)	3 (33)
Mechanism of Injury, n (%)		
Contact	3 (38)	6 (67)
Non-contact	5 (62)	3 (33)

Reason for incomplete hop test, n (%)*		
Apprehension	4 (50)	3 (33)
Stiffness	4 (50)	2 (22)
Valgus	2 (25)	3 (33)
Unstable	0 (0)	3 (33)
Graft Failure	0 (0)	1 (11)

Abbreviations: SD = standard deviation. *Note: for some patients the test was stopped for more than one reason

5.2.3 Fear Avoidance Beliefs Questionnaire – Physical Activity Subscale (FABQ-PA)

We found no significant difference in Fear Avoidance Beliefs Questionnaire – Physical Activity subscale scores between jumpers and non-jumpers within each treatment group (Table 3).

Table 3: Fear Avoidance Beliefs Questionnaire – Physical Activity (FABQ-PA) scores between jumpers and non-jumpers in each treatment group.

Group	Jumpers (n = 30) Mean ± SE	Non-Jumpers (n = 17) Mean ± SE	Mean Difference (95% CI)	p-Value
ACL (n = 24)	11.4 ± 1.6	11.6 ± 1.6	0.2 (-5.1 to 5.5)	0.94
ACL plus LET (n = 23)	10.3 ± 1.1	14.1 ± 1.8	3.8 (-0.3 to 7.9)	0.07

Abbreviations: SE = standard error, CI = confidence interval

5.3 Primary Outcome: Peak Knee Abduction Moment (KAM)

A total of 30 patients completed the DVJ test at six months following surgery (16 ACL alone, 14 ACL plus LET). Patients in the ACL plus LET group demonstrated a lower peak KAM during the entire stance phase than the ACL alone group; however, the difference between groups was not statistically significant (Table 4). Using the total FABQ-PA score as a covariate, the adjusted mean peak KAM was also not statistically significant between the ACL group (1.30 %BW×ht) and the ACL plus LET group (1.16 %BW×ht) (Adjusted Mean Difference, -0.14; 95% CI, -0.54 to 0.821, $p = 0.67$).

5.4 Secondary Outcome Measures

5.4.1 Kinetics

Differences in peak KFM, peak KRM and peak VGRF were not statistically significant between the ACL alone and ACL plus LET group (Table 4).

Table 4: Kinetic outcomes for patients undergoing ACL reconstruction with or without an LET. A comparison of the injured limb between groups.

Kinetic Variables	ACL Alone (n = 16) Mean ± SE	ACL plus LET (n = 14) Mean ± SE	Mean Difference (95% CI)	p-Value
Stance Phase:				
Peak KAM (%BW×ht)	1.31 ± 0.22	1.14 ± 0.24	0.17 (-0.50 to 0.84)	0.60
Peak KFM (%BW×ht)	4.79 ± 0.31	4.55 ± 0.30	0.23 (-0.65 to 1.11)	0.59
Peak KRM (%BW×ht)	0.55 ± 0.08	0.45 ± 0.07	0.10 (-0.12 to 0.32)	0.37
Peak VGRF (BW)	1.25 ± 0.04	1.31 ± 0.06	-0.06 (-0.21 to 0.08)	0.36

Abbreviations: SE = standard error, CI = confidence interval

5.4.2 Kinematics

There were no significant differences in knee abduction angle, knee flexion angle or knee internal rotation angle between treatment groups at initial contact. Similarly, there were no significant differences in peak kinematic values during stance phase between patients who received an ACL reconstruction alone, and patients who received an ACL reconstruction plus LET (Table 5).

Table 5: Kinematic outcomes for patients undergoing ACL reconstruction with or without an LET. A comparison of the injured limb between groups.

Kinematic Variables	ACL Alone (n = 16) Mean ± SE	ACL plus LET (n = 14) Mean ± SE	Mean Difference (95% CI)	p-Value
Initial Contact:				
Abduction Angle (°)	1.84 ± 0.95	0.62 ± 1.09	1.22 (-1.73 to 4.17)	0.40
Flexion Angle (°)	11.84 ± 1.13	8.93 ± 1.11	2.91 (-0.36 to 6.18)	0.08
Internal Rotation Angle (°)	-22.34 ± 2.00	-17.88 ± 3.13	-4.46 (-12.15 to 2.96)	0.23
Stance Phase:				
Peak Abduction Angle (°)	10.53 ± 2.33	5.14 ± 2.05	5.39 (-1.05 to 11.83)	0.10
Peak Flexion Angle (°)	86.05 ± 3.35	89.79 ± 3.40	4.79 (-13.55 to 6.08)	0.44
Peak Internal Rotation Angle (°)	-1.99 ± 2.62	2.87 ± 2.44	4.86 (-12.27 to 2.55)	0.19

Abbreviations: SE = standard error, CI = confidence interval

Chapter 6

6 Discussion

The purpose of this thesis was to compare the six month landing mechanics of a drop vertical jump (DVJ) between patients who underwent an anterior cruciate ligament (ACL) reconstruction with or without lateral extra-articular tenodesis (LET). We assessed several kinetic and kinematic outcomes that to provide a comprehensive evaluation of knee biomechanics in three dimensions. Our preliminary analysis found no significant differences in dynamic knee stability between the two treatment groups.

We used the peak knee abduction moment (KAM) during the stance phase of a DVJ as our primary outcome because it is the strongest documented biomechanical predictor of future ACL injury.^{132,149,157,159} Previous work by Myer et al. has shown that individuals who demonstrate high KAMs (> 25.3 Nm) during the stance phase of a DVJ task are at a 6.8% increased risk of subsequent ACL injury compared to a 0.4% risk if below this threshold value.¹⁵⁹ Although we did not find significant differences in normalized peak KAM values between those who received an ACL reconstruction alone and those who received an ACL reconstruction plus LET, both groups demonstrated an average non-normalized peak KAM below the 25.3 Nm threshold proposed by Myer et al. These findings suggest that both treatment groups demonstrate safer frontal plane DVJ kinetics than the high risk individuals identified in previous studies.

We found no significant differences in any of the other kinematic and kinetic variables at initial contact or stance phase between the two treatment groups at six months following surgery. Several studies have suggested that biomechanical abnormalities at the knee still exist among young athletes following ACL reconstruction, and it is believed that these persisting deficits may increase the risk of graft failure.^{144,147,148} We did not conduct pre-injury DVJ testing and therefore cannot comment on the biomechanical changes that occurred as a result of each treatment method. However, when comparing our results to the literature, we found multiple similarities and differences between our values and the values considered to be clinically important from previous research.

Firstly, several studies have examined the landing biomechanics of athletes following ACL reconstruction and the majority have suggested that a high knee abduction angle is associated with an increased risk of re-injury.^{147,10,11} Although we found no difference between treatment groups, there was a trend towards lower risk frontal plane kinematics among patients who received an ACL plus LET. More specifically, when comparing our findings to previous research, our ACL plus LET group demonstrated peak knee abduction angles that were more similar to healthy controls than they were to other ACL reconstructed patients.^{10,11} Our ACL alone group, however, demonstrated peak knee abduction angles that were consistent with the results of conventionally reconstructed patients of previous studies.¹⁰ Therefore it's possible that patients who received an ACL plus LET reconstruction may exhibit closer-to-normal landing kinematics in the frontal plane than patients who received an ACL reconstruction alone, but at this time our sample size is insufficient to make any definitive conclusions.

Secondly, there were no differences in sagittal plane knee kinematics between our two treatment groups. However, both groups demonstrated higher knee joint flexion angles than the values demonstrated in the current literature.¹⁵³ Knee joint flexion has been described as a method of force attenuation upon contact with the ground.^{144,164} Individuals who land with more knee flexion during a DVJ are better able to dissipate ground reaction forces transmitted to the knee.^{144,10,164} Conversely, individuals who land with lower flexion angles during a DVJ have been shown to demonstrate higher anterior tibial shear force (ATSF) at the knee and subsequently increased loads through the ACL.^{10,146} Although we cannot attribute this biomechanical adaptation to either surgical intervention, it is interesting to note that both treatment groups in our study demonstrated favorable neuromuscular control in the sagittal plane. These findings may be attributed to the instructions conveyed by the kinesiologist during the preceding hop test. A “soft landing” by means of increased knee flexion was commonly reinforced during hop testing. It is likely that these movement adaptations were carried through and subsequently demonstrated during DVJ testing.

More typically, rotational knee stability is assessed within a clinical setting using the lateral pivot shift test,⁷¹ whereas antero-posterior stability is assessed using the Lachman

or anterior drawer test.^{71,165} Although conventional ACL reconstructive techniques have demonstrated adequate control of antero-posterior tibial translation, some studies have noted abnormal tibial rotation in the transverse plane and high residual pivot shift rates when compared to the contralateral knee.^{7,12-14} Alternatively, the combined ACL plus LET reconstruction has been commended for its ability to reduce the rates of the residual pivot shift phenomenon.^{23,166,167}

From a practical standpoint however, the lateral pivot shift test does not take into account the additional contribution to overall knee stability offered by surrounding passive structures and dynamic muscular stabilizers. As an autologous graft, harvested from the iliotibial band, the LET is created at the expense of a dynamic stabilizer. It is important to understand the true effects of this tradeoff and whether the role of the LET outweighs the contribution of its parent structure. At this early analysis, we did not find significant differences in transverse knee biomechanics between the two treatment groups. It is therefore our preliminary conclusion that the additional LET procedure does not adversely affect rotational knee stability during a dynamic functional task. Conversely, at this time, we cannot attribute any additional passive rotatory knee stability to the LET above and beyond what is provided by the ACL reconstruction alone.

It is important to note, however, that *in vivo* biomechanical analysis of transverse knee kinematics is not a reliable measure of true rotational knee stability.¹⁶⁸⁻¹⁷¹ Virtual joint centers, and subsequent virtual body segments, are a prediction of bony movements based off of superficial markers and predetermined anthropometric measures. The values for transverse knee kinematics obtained in our analysis include the relative motion of superficial biomarkers, not the desired movement of the underlying bones. Thus, subtle transverse kinematics at the articulating surfaces of the tibia and femur are typically over-represented during three dimensional motion analysis reflecting the greater movements of skin and muscle tissue compared to underlying bone.^{170,172}

The secondary objective of our study was to determine whether patient reported fear associated with physical activity (FABQ-PA score) was different between those who could and could not perform DVJs at six months following surgery. A registered

kinesiologist permitted patients to perform drop jumps upon successful completion and safe execution of a hop test. Within our study cohort, hop tests were stopped if patients demonstrated apprehension, stiffness, valgus collapse or instability to a degree that was deemed unsafe by our kinesiologist. We predicted that patients who did not finish the hop test (non-jumpers) would report higher fears associated with physical activity than those who were able to finish the test (jumpers). We based our prediction off of the previous work by Michael D. Ross (2010) who found that fear avoidance beliefs explained a significant amount of variance in functional levels (as determined by knee outcome survey (KOS), the activities of daily living scale (ADLS) and the sports activity scale (SAS) scores) among a group of patients following ACL reconstruction.¹⁷³ The results from Ross' study suggest that fear-avoidance beliefs following ACL reconstruction can potentially adversely influence functional levels and ultimately athletic performance.¹⁷³ With this in mind, we expected that the non-jumpers in our study sample would score higher on the FABQ-PA than the jumpers.

Upon evaluating the results, we did find a trend towards higher FABQ-PA scores among non-jumpers in the ACL alone group; however, the differences between jumpers and non-jumpers in both treatment groups were not statistically significant. In 2008, Chmielewski et al. suggested that fear of movement and re-injury decreases with increased time from ACL reconstruction.¹⁷⁴ Since most patients gradually return to sport between nine and twelve months following surgery (as per the Fowler Kennedy ACL rehabilitation protocol, Appendix B), the six month time point at which we administered the questionnaire may be too early to capture the true fear avoidance beliefs associated with physical activity. We expect to see more accurate results at the 12 month time point, when most patients have returned to sport. We also anticipate an increase in precision of scores as our sample size continues to increase.

6.1 Limitations

A limitation of this study is our small sample size. Our small sample size is reflected in the wide confidence intervals around our estimates of the effect of the treatment.

However, this was a preliminary analysis and a larger sample size upon completion of the study, will provide a greater certainty around our measured outcomes. Another limitation of our study is with its applicability. Specifically, all subjects were treated at the Fowler Kennedy Sport Medicine Clinic, which is a tertiary care centre with expert surgeons located in Southwestern Ontario. Further, the majority of patients were elite athletes.

Reliability of biomechanical outcomes, specifically during jumping maneuvers, is not well defined in the literature. Although three-dimensional motion analysis is considered the gold standard for assessment of lower extremity movement biomechanics, there are several inherent sources of error including joint center estimations, marker placement and skin/soft tissue movement artifacts.^{172,175} These factors have been shown to reduce the accuracy and precision of the calculated joint angles and moments, particularly when assessing the subtle axial movements of the underlying bones.^{168,172,175} An attempt to eliminate soft tissue artifacts via percutaneous bone fixtures has proven to be successful; however, this method is highly invasive and likely alters joint motion kinetics and kinematics during functional movement tasks.¹⁷⁶ Additionally, biplanar videoradiography has been used to assess knee joint biomechanics during a dynamic sport specific maneuvers.¹⁶⁸ However, the imaging volume associated with biplanar videoradiography is small, therefore, it may be difficult to capture large range of motion movements like the DVJ. Furthermore, the equipment is not readily available and there is an increased risk to patient safety associated with x-ray exposure.

Another limitation in our study is specific to the FABQ-PA questionnaire for our specific population of active patients at a high risk of graft failure. When designing this study, we chose the FABQ-PA as it had been previously validated in a group of patients following ACL reconstruction. However, all participants in the validity study were members of an academic military academy where the differences between the psychological and physical characteristics of individuals inside and outside the military may limit the validity of the questionnaire. For example, the choice of modified descriptors within the questionnaire (i.e. “walking” and “kneeling”) do not represent activities of particular concern (that may invoke feelings of fear) in our specific population. Therefore to improve the validity of

the questionnaire, descriptors may need to include more aggressive movements like “jumping” and “cutting”.

The inclusion criteria for performing the DVJ was restricted to participants who could complete the preceding hop test, which meant that 17 patients were excluded.

Unfortunately, this meant that any aberrant biomechanics also went unobserved, which may mean that the average biomechanical values presented in our study underrepresent the true extent of high-risk biomechanical movements within our population of interest. We administered this protocol with patient safety in mind. At six months following surgery, many patients had not yet reached the stage in rehabilitation that required them to perform ballistic movements like the hop test or the DVJ. Therefore we did not push patients beyond what they were capable of doing. We anticipate that the majority of patients will be able to perform the DVJ at 12 months following surgery and it's important to emphasize that the proportion of participants unable to participate in the DVJ trials was balanced between the groups.

Chapter 7

7 Conclusions

We found no significant differences in the landing biomechanics between patients who received an ACL reconstruction with or without LET. However, since these findings are the preliminary results of a larger continuing study, results are underpowered and no definitive conclusions can be drawn at this time. More conclusive results will be presented upon the completion of the trial.

7.1 Future Directions

For this study, we will continue collecting data until the appropriate sample size is reached. In doing so, we will reduce the uncertainty around our estimates of effect size. Furthermore we will include the results of the 12 and 24 month follow-up visits. We anticipate that more patients will be able to complete the hop test and subsequent DVJ assessment at later follow-up dates. Not only will this capture the biomechanical values of patients who were unable to jump at six months postoperative, but it will also provide us with more information regarding the long-term benefits of each surgery and change scores between visits.

Future research should include comparisons to the uninjured limb. Several studies have acknowledged the importance of biomechanical limb symmetry in re-injury prevention following ACL reconstruction.^{153,137,145} Therefore inclusion of a limb symmetry index in our analysis will provide a more in depth review of within patient changes as a result of each surgical intervention. It would also be beneficial to look at the kinetic and kinematic changes at the hip as a result of each intervention. Adduction and Internal rotation at the hip are characteristic biomechanical components of the valgus collapse.^{137,156,177,178} Since the iliotibial band (and the associated tensor fascia lata) plays a role in eccentrically controlling both hip adduction¹⁷⁹, it would be interesting to see the effects of the LET procedure on hip biomechanics and subsequent knee movement. Furthermore, analysis of

EMG data during the DVJ could provide us with important information regarding muscle activation throughout the jump. In order to attach the LET to the femur, the vastus lateralis must be retracted. If damaged, muscle recruitment and ultimately landing biomechanics may be adversely effected.

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Appendices

Appendix A: UWO REB 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 IRB 00000940

[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
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Appendix B: Letter of Information and Consent



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

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Patient Initials: _____

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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.)



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 Responsible for Obtaining Informed Consent	Date



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

Appendix C: Fowler Kennedy Physiotherapy Following ACL Reconstruction Protocol



fowlerkennedy.com

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)⁽⁵⁴⁾. 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 glycolytic 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. semitendinosus/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 (semitendinosus / 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 through 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).

0-2 WEEKSLEFS 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 ¼ 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⁾
 - **only if: 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 or 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

LEFS range: 55-66

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

Quadriceps:

- 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)**}

Hamstrings/Gluteals:

- 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 ¼ 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 WEEKSLEFS 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)

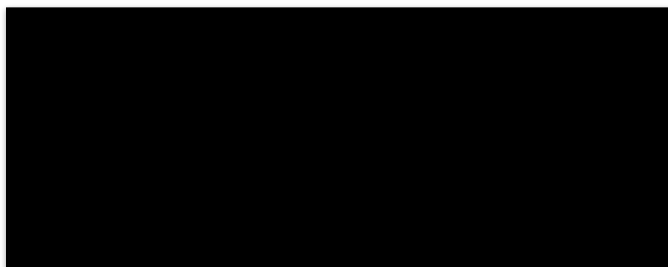
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Appendix D: Data Collection Form

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

Appendix E: Fear Avoidance Beliefs Questionnaire: Physical Activity Subsection

PID: _____

Date: _____

Database ID: _____

Subject #: _____

 Followup: 6 months 1 year 2 years

FEAR AVOIDANCE BELIEFS QUESTIONNAIRE: PHYSICAL ACTIVITY (FABQPA)

Here are some of the things which other patients have told us about their pain. For each statement please circle any number from 0 to 6 to say how much physical activities such as walking, running and kneeling affect or would affect your knee pain.

	COMPLETELY DISAGREE			UNSURE		COMPLETELY AGREE	
1. My Pain was caused by physical activity	0	1	2	3	4	5	6
2. Physical activity makes my pain worse	0	1	2	3	4	5	6
3. Physical activity might harm my Knee	0	1	2	3	4	5	6
4. I should not do physical activities which (might) make my pain worse	0	1	2	3	4	5	6
5. I cannot do physical activities which (might) make my pain worse	0	1	2	3	4	5	6

 Patient Initials: _____
Version: April 4th, 2016

Curriculum Vitae

NAME: MICHAL DANILUK

EDUCATION:

Master of Science: Kinesiology, Integrative Biosciences,
Collaborative Musculoskeletal Health Research
Western University, London, ON, Canada.
September 2014 – August 2016

Bachelor of Arts: Honors Specialization in Kinesiology
Western University, London, ON, Canada.
September 2009 – May 2013

HONORS AND AWARDS:

Western University Western Graduate Research Scholarship (\$5,250/year)
2014 – 2016

Western University Collaborative Musculoskeletal Health Research Stipend (\$750)
2016

Western University CMHR Transdisciplinary Bone & Joint Training Award (\$10,000)
2015

Western University Dean's Honor List
2010 – 2013

Western University Western Scholarship of Distinction (\$1000)
2009

RESEARCH EXPERIENCE

Western University Drop Vertical Jump Landing Mechanics Following Anterior
Graduate Student Cruciate Ligament Reconstruction With and Without Lateral
2014 – 2016 Extra-Articular Tenodesis
Supervisors: Dr. Dianne Bryant
Dr. Alan Getgood
Dr. Trevor Birmingham

Western University STABILITY Study: A Multicentre Randomized Clinical Trial
Graduate student Comparing Anterior Cruciate Ligament Reconstruction With and
2014 – 2016 Without Lateral Extra-Articular Tenodesis in Individuals at High
Risk of Graft Failure.

RELATED WORK EXPERIENCE:

Western University Kin 3336A/B: Practical Aspects of Athletic Injuries
Teaching Assistant Professor Dave Humphreys
 2015 - 2016 Lecturer: *Platelet-Rich Plasma (PRP) – A Review of the Literature*
 Lecturer: *The Rotator Cuff – Functional Anatomy, Biomechanics and Injury management*

PRESENTATIONS

Poster Presentation *A Randomized Clinical Trial Comparing Knee Abduction Moments During Drop Vertical Jumps Following Anterior Cruciate Ligament Reconstruction With and Without a Lateral Extra-Articular Tenodesis*
 April 2016 Western's 2016 Bone & Joint Conference, London, ON

Oral Presentation *A Prospective Study Comparing Landing Mechanics During Drop Vertical Jumps Following Anterior Cruciate Ligament Reconstruction With and Without a Lateral Extra-Articular Tenodesis*
 May 2015 Bodies of Knowledge Conference, University of Toronto

Poster Presentation *A Randomized Clinical Trial Comparing Knee Abduction Moments During Drop Vertical Jumps Following Anterior Cruciate Ligament Reconstruction With and Without a Lateral Extra-Articular Tenodesis*
 May 2015 Western's 2015 Bone & Joint Innovation Retreat, London, ON

Poster Presentation *A Randomized Clinical Trial Comparing Knee Abduction Moments During Drop Vertical Jumps Following Anterior Cruciate Ligament Reconstruction With and Without a Lateral Extra-Articular Tenodesis*
 March 2015 FHS Research Day, Western University

Oral Presentation *Landing Mechanics Following ACL Reconstruction With and Without a Lateral Extra Articular Tenodesis*
 February 2015 Fowler Kennedy Sport Medicine Clinic Research Rounds, Western University