DOUBLE BUNDLE ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION: EVALUATION OF KNEE FLEXION ANGLE AND OVER-THE-TOP TECHNIQUE

by

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DOUBLE BUNDLE ACL RECONSTRUCTION: EVALUATION OF KNEE FLEXION ANGLES AND OVER-THE-TOP TECHNIQUES

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Double bundle anterior cruciate ligament reconstruction (DB-ACLR) has recently gained popularity in Europe and Japan. This procedure utilizes two separate tissue grafts to replicate the two functional bundles of the intact anterior cruciate ligament (ACL). Therefore it is believed that the two grafts will be able to restore both the anterior and rotatory laxity to that of an intact knee.

However, as in the case of a traditional single bundle ACL reconstruction, there are several variables that can affect the outcome. The knee flexion angle at which each of the two grafts are fixed, is one such variable. Since it is understood that an improper force distribution among the two grafts could lead to the failure one or both of the grafts, it is important to fix the grafts, such that the in situ force of each graft does not exceed that of their respective intact bundle. Therefore, one of the objectives of this thesis is to study if and how the knee flexion angle for graft fixation affects the force distribution of the two grafts in DB-ACLR.

A second concern regarding DB-ACLR is related to the complications of drilling a second femoral tunnel. Not only can tunnel placement become more complex, but more problems may also arise in the event of a revision surgery. Therefore, a DB-ACLR procedure that utilizes only a single tibial and femoral tunnel will be investigated. In this procedure, a single femoral tunnel will be created for the PL graft, while the second graft will be fixed on the lateral femoral epicondyle via a staple (fixation protocol PL+OTT).

In order to study the effect of the knee flexion angle of graft fixation, as well as the PL+OTT procedure, knee kinematics will be collected for the intact, ACL(-), and reconstructed knees under both a 134 N anterior tibial load, as well as a combined rotatory load of 10 N-m valgus, and 5 N-m internal/external tibial rotation. Lastly, the in situ force of the intact ACL, as well as the intact bundles will be determined, and compared with the in situ force of the grafts.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

Over the last three years, I have grown tremendously as a person, as well as a researcher. My growth is directly due to the amazing people that I have worked with at the MSRC. I would like to thank Dr. Savio L-Y. Woo for this opportunity, which has made me into the person I am today. I know that I have made lifelong friends here, and will always look back at these years with joy and humor.

I wish I could acknowledge all of the people who have helped me, since there have been many, however there are a few people that I feel a need to single out. Dr. Steven Abramowitch has been an amazing mentor and friend to me, and I look forward to hearing about the great things that I know he will accomplish in the future. Another person who has greatly helped me achieve my dreams and has influenced me as a person is Dr. Alejandro Almarza. I will definitely never forget the dubious duo of Steve and Alex, and will always be grateful for all that they have done for me.

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Lastly I would like to thank my family. Without them, none of my accomplishments would have been possible, nor would any of it have any meaning. My parents, Rafiqul and Zarina have always loved and supported me, and I am truly blessed to have them in my life. I also need to express my love and gratitude to Uncle, Auntie, Niti, Pappu, and my little sister Nira.

1.0 MOTIVATION

The anterior cruciate ligament (ACL) is the most frequently ruptured ligament of the knee. Roughly one in 3,000 people are affected annually in the United States [1]. This translates roughly into 150,000 ACL tears just in the US alone. Unlike other ligaments and tendons, an ACL tear cannot heal on its own. This leaves the patient with an unstable knee, and even "giving way" episodes. If left untreated, it can lead to damage to the surrounding soft tissues, especially the meniscus which can ultimately lead to an early onset of osteoarthritis [2-5]. In most cases, for young and active patients, surgical reconstruction is recommended to restore knee stability. In the United States, it is estimated that around 100,000 ACL reconstructions are performed annually, using tissue autografts and allografts [6]. The direct cost for these operations is estimated to be over $1 billion.

The primary goal of an ACL reconstruction is to restore knee stability. Unfortunately, both short and long term clinical outcome studies show that there exists 11-32% of patients with less than satisfactory outcomes after their reconstructions [7-9]. Therefore, to date, reconstructions have yet to be able to accurately reproduce the complex anatomy and function of the native ACL in stabilizing the knee joint in multiple degrees of freedom. In order to reproduce the functions of the intact ACL, the replacement graft must function in a manner that is similar to the native ACL. How the graft is fixed is a major contributing factor to the outcome of any ACL reconstruction. Therefore in our research center, many laboratory studies have been conducted that have looked at how various fixation methods affect the biomechanical outcome.

Traditional reconstructions have looked to replace the larger anteromedial (AM) bundle of the intact ACL, while choosing to ignore the smaller posterolateral (PL) bundle. However biomechanical studies have shown that when the knee is subjected to anterior tibial loads, at least half of the load was carried by the PL bundle when the knee is near extension. Therefore it was found that for a single bundle procedure, a more lateral graft placement around the 10 o'clock position, which is anatomically closer to the femoral insertion of the PL bundle could improve rotatory stability [10]. However, even with a lateral placement, a single bundle reconstruction still does not replicate the functional anatomy of the two bundle ACL. Therefore, a later study compared a double bundle ACL reconstruction, in which two separate grafts are used to replace the AM and PL bundles, with a single bundle reconstruction [11]. The double bundle reconstruction had an overall in situ force significantly different from the single bundle reconstruction, but was not significantly different from the intact ACL under an applied anterior tibial load ($p<0.05$). Finally a third study was conducted which compared the performance of a double bundle procedure to that of a lateral PL bundle reconstruction [12]. A previous study had shown that the PL bundle reconstruction helped restore rotatory laxity to that of the intact knee. However the double bundle procedure was able to restore both the rotatory laxity as well as the anterior laxity throughout the whole range of flexion. This is because a double bundle procedure addresses both anterior and rotatory laxity by replicating the two functional bundles of the intact ACL.

2.0 BACKGROUND

2.1 KNEE ANATOMY

The knee joint consists of four bones: the tibia, femur, fibula, and patella. The tibia extends from the knee joint to the ankle, while the fibula runs parallel to the tibia on the lateral side. The femur extends from the hip to the knee joint. The head of the femur fits within the acetabelum, while at the knee joint, the femoral condyles glide on top of the tibial plateau. The patella is a sesamoid bone that is found within the quadriceps and patellar tendon. It glides within the trochlear groove of the femur to make up the patellofemoral joint. In between the tibiofemoral joint lies the lateral and medial menisci, which conforms to the surface of the tibial plateau. There are four main ligaments of the knee: the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial collateral ligament (MCL), and the lateral collateral ligament (LCL).

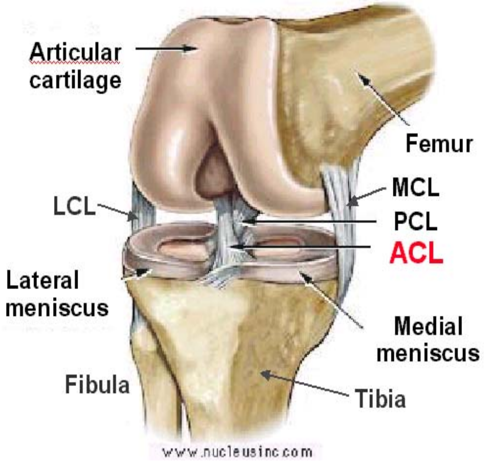

Figure 1. Knee Anatomy

The ACL and PCL cross over one another inside the joint to connect the femur and tibia. Both are intra articular and extrasynovial. The ACL is the primary restraint for anterior motion of the tibia, while the PCL limits posterior motion. The MCL and LCL function to limit medial and lateral translation as well as varus/valgus rotation. However due to its complex anatomy the ACL also controls internal/external rotation, and is a secondary stabilizer for varus/valgus torques.

2.2 ACL STRUCTURE AND FUNCTION

The anterior cruciate ligament has a complex anatomy which allows for its unique function in restraining anterior translation, as well as tibial rotations. The ACL attaches to the posterior part of the inner lateral femoral condyle. From the femoral insertion, the ACL runs anteriorly, medially, and distally to the tibial insertion. The length of the ACL is anywhere between 22 to 41 mm, and the width ranges from 7 to 12 mm [13]. The cross sectional area is irregular, and increases from the femoral attachment to the tibial insertion [14]. However, it is important to note that the shape of the ACL changes with the knee flexion angle. This is because the ACL consists of two functional bundles: the anteromedial (AM) and posterolateral (PL) bundles (Figure 2). The bundles are named after their tibial insertions [15]. The two bundles are not isometric in flexion/extension but experience different patterns of length change throughout the range of passive knee flexion. The PL bundle lengthens and becomes taut near extension, while the AM bundle is slack. Conversely, the AM bundles lengthens and becomes taut as the knee is flexed.

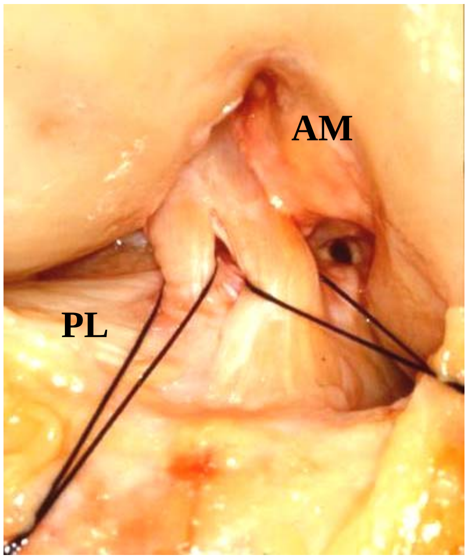

Figure 2. AM and PL bundle intact ACL

Biomechanical studies have shown how the two bundles function under externally applied loads to the knee joint. Under a 134 N anterior tibial load, the PL bundle generally carried more load at full extension and at 15˚ of knee flexion, whereas the AM bundle carried some load throughout the entire range of motion, but especially at deeper flexion [16, 17]. In general, beyond 30˚ of knee flexion, the PL bundle does not contribute to anterior stability. Under combined rotatory loads of 10 N-m valgus and 5 N-m internal/external tibial torques, the PL bundle carried a significant load at 15˚ degrees of knee flexion. Although the AM bundle carried a higher load (30±15 N) than the PL bundle (21±11 N), it proves that the PL bundle plays a significant role in controlling rotatory stability.

2.3 TREATMENT OF ACL DEFICIENCY

In most cases, conservative treatment is not sufficient to regain knee stability and function. A lack of treatment can lead to secondary injuries to other soft tissues, especially the meniscus. The onset of early osteoarthritis is common after an ACL rupture. Reconstruction of the ACL with a tissue autograft or allograft is most commonly recommended, especially for young and active populations [18]. Traditionally, several types of grafts are used: bone patellar tendon bone, hamstrings tendons (semitendinosus and gracilis), quadriceps tendon, and Achilles tendon [19, 20].

Due to recent evidence that traditional ACL reconstructions fail to restore rotatory stability, researchers have started to investigate double bundle ACL reconstruction, which utilizes two separate tissue grafts to replicate the two functional bundles of the intact ACL [11, 21, 22]. For a double bundle procedure, hamstrings tendons, either autografts or allografts are most commonly used as replacement grafts.

2.4 VARIABLES IN DOUBLE BUNDLE ACL RECONSTRUCTION

The use of two separate grafts to reconstruct the ACL adds additional variables as well as complications to the traditional single bundle procedure. Variables such as graft choice, graft fixation, tunnel placement, initial graft tensioning have been studied for traditional single bundle procedures, however the affect of each of these variables remain unknown for double bundle ACL reconstruction. Due to the additional complications, many researchers and clinicians have expressed concern regarding potential problems that may arise from attempting a double bundle procedure.

In 2005, at the AAOS symposium, it was shown that the knee flexion angle for graft fixation varied from full extension to 90° for the AM graft, while the range for the PL graft was from full extension to 60° of knee flexion [21-27]. The large variation among the knee flexion angles proved that their existed a lack of understanding regarding how the knee flexion angle for graft fixation would affect knee stability as well as the force distribution in the grafts. For instance, for a single bundle procedure, a study by Hoher et al., has shown that fixation of the graft at 30° of knee flexion under an applied 67 N posterior tibial load resulted in a more stable knee throughout the range of knee motion [28]. A clinical study also compared the difference in knee stability and range of motion after ACL reconstruction with a hamstring graft. In this study it was found that the range of motion was better with the graft fixed at full extension, however the knee stability was significantly better with the graft fixed at 30° of knee flexion [29]. Since the knee flexion angle at which the graft is fixed is important in single bundle reconstruction, it stands to reason that the knee flexion angle for graft fixation is equally important regarding the outcome of a double bundle ACL reconstruction.

2.5 CONCERNS WITH DOUBLE BUNDLE ACL RECONSTRUCTION

Although DB-ACLR has the advantage of providing both rotatory stability in addition to anterior stability compared to a single bundle reconstruction, there are still concerns regarding the success of this procedure, as well as potential problems. Tunnel placement is a crucial component for the success of any ACL reconstruction. Several researchers have found that the primary cause of graft failure or unsuccessful outcome is due to improper tunnel placement [30-32]. It has been shown that the position and placement of the femoral tunnel is especially important for a successful reconstruction. Laboratory studies have shown the sensitivity of the femoral tunnel placement in regards to graft performance. Therefore, in a double bundle ACL reconstruction, the correct placement of two femoral tunnels could cause significant complications during surgery.

Recently a clinical study has done a 1 year follow up on patients who received a double bundle procedure. They found that 43% of patients had tunnel breakage on the tibial side due to either improper tunnel drilling, or as a result of tunnel widening [33]. The rate of tunnel widening on both the tibial and femoral side was comparable to those reported for single bundle procedures. The authors concluded that a double bundle ACL reconstruction was not for every patient, and that extra care should be taken when placing the tunnels.

2.6 BIOMECHANICS OF THE ACL

2.6.1 Kinematics of the Knee

The knee joint has 6 degrees of freedom (DOF) motion that is defined by three translations and three rotations along its anatomical axes [34]. Within the knee joint, there are three axes that are referred to as the femoral epicondylar axis, the tibial shaft axis, and the floating axis, which is perpendicular to the other two axes. Translation along these three axes will lead to medial-lateral (M-L) translation, proximal-distal (P-D) translation, and anterior-posterior (A-P) translation, respectively. The rotations about these axes are flexion-extension (F-E), internal-external (I-E), and varus-valgus (V-V), respectively. In order to understand the function of ligaments and tendons, it is important to determine how each ligament contributes to knee stability in all degrees of freedom.

In addition to accurately measuring the knee kinematics, it is necessary to know the in situ forces in ligaments in order to better understand knee ligament function. The ability to gain as much information in the normal knee allows for better diagnosis of injury, improved surgical techniques, as well as rehabilitation protocols. Therefore as in the case for kinematics, an accurate technique is required to measure the in situ force of ligaments and other soft tissues.

Some early techniques involved contact of the instrumentation with the ligament being measured. These apparatus that attached transducers directly to the ligament include the buckle transducer, differential variable resistance transducer (DVRT), implantable force transducer (IFT), and various strain gauges. The buckle transducers pass the ligament through a “buckle which moves when the tension in the ligament increases. The DVRT and IFT are directly implanted into the ligamentous tissue.

The previously described devices work through a similar concept that increases in ligament tesnsion, increase the transverse force on the implanted device, which in turn leads to an increase in output voltage. This output voltage is translated to an in situ force during post test in vitro calibration. The limitations of these devices include disruption of the ligament fibers due to contact, prevention or limitation of some knee motion, and a lack of direct force measurement. The calibration test is not necessarily performed in exactly the same situation as the test measurements. Markolf et al., recently attached a specially designed force transducers beneath the insertions of the cruciate ligaments. While technically a non-contact method with respect to the ligament midsubstance, a large drill hole (25mm) was needed, which damaged the insertion sites. This method also requires the assumption that the center of the jig is the point of application for external loading conditions.

As far as non-contact methods, the use of a kinematic linkage and materials testing machine was fairly successful. This method allowed for a whole cadaveric knee to be tested. The kinematic linkage would record the positions the knee was while the testing machine would apply the load and record the forces. After repositioning the knee (either change in flexion angle or loading condition), the new kinematics and force would be determined. A cutting study could then be performed. This method worked well for 1-DOF testing, but through the use of custom made clamps and jigs, additional DOFs were added (up to 5-DOF). However, the repeatability of the motion, most importantly the starting reference position, was in doubt with this method limiting repeatability.

In our research center a robotic manipulator was combined with a universal force-moment sensor (UFS) in order to collect both knee kinematics and determine direct in situ forces in ligaments without contacting the tissue or dissection of the joint. In theory, this testing system is similar to the kinematics/materials testing machine method of the past, in that the specimen is put through a set of kinematics and the force is measured each time a structure is transected. However, the ability to have multiple DOF joint motion with great repeatability is provided with robotic technology. Additionally the robotic/UFS testing system allows researchers to apply multiple and complex loading conditions to the same knee specimen, and thus eliminate or reduce interspecimen variability.

2.6.2 Specifications of the Robotic/UFS Testing System

The experimental data collection was done using a 6 DOF robotic manipulator (Unimate, PUMA model 762) and a universal force-moment sensor (Figure 3). The robotic/UFS testing system is able to operate in both force control and position control modes. The force controls are possible via a force-feedback from the UFS. Therefore external loads can be applied to a knee joint at a chosen flexion angle, and the resulting 5 DOF kinematics of the knee, as well as the in situ force in the soft tissues can be determined [35]. The robotic manipulator used in this study uses a six joint, serial articulated position-controlled device [36]. It has a position and orientation repeatability in a single dimension of less than 0.08 mm and 0.2 degrees, respectively. This then corresponds to a position repeatability in three dimensions of 0.2 mm. In terms of force capability, the robot can handle greater than 450 N. The universal force-moment sensor (JR3, CA, model 4015) is capable of measuring three forces and three moments along and about a Cartesian coordinate system fixed with respect to the sensor [34]. The UFS has a working capacity of ±900 N along its z axis, and ± 450 N along its x- and y-axes, as well as ± 50 N-m for moments. The UFS has a repeatability of less than 0.2 N and 0.01 N-m for forces and moments, respectively.

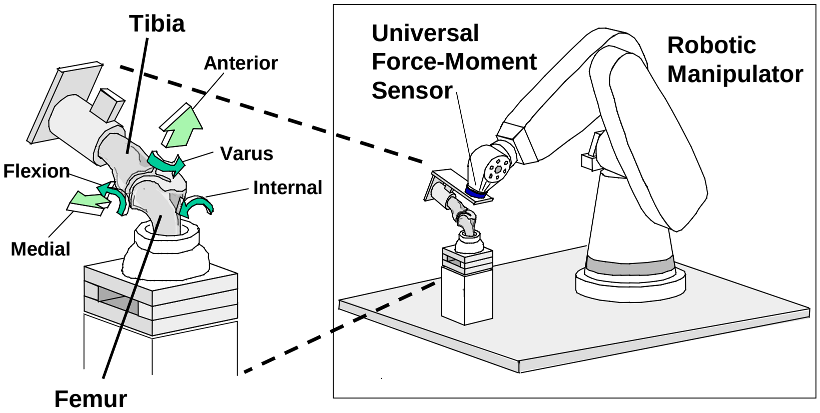

Figure 3. Robotic Universal Force Moment (UFS) Testing System

2.6.3 Coordinate Systems and Transformations

In order to apply loads or measure the forces and moments on the tibia, it is necessary to describe the orientation and position of the end-effector of the robotic manipulator, as well as the location of the tibia and femur. In order to determine a relationship throughout the entire testing system, five coordinate systems are required: the global coordinate system of the robotic manipulator, the local tool coordinate system or the robot, the UFS coordinate system, and the femoral and tibial anatomic coordinate systems [37]. The first, C_{rg}, is the global coordinate system of the robotic manipulator, which is fixed relative to the base of the robot. Any end-effector motion has to be defined with respect to the global coordinate system. At the origin, the z-axis is oriented vertically, while the x- and y-axes are parallel to the ground. The coordinate system describes the position and orientation of the end-effector of the manipulator is what is described as the local or robotic tool coordinate system, C_{tool}. For the robotic tool coordinate system, the z-axis is oriented perpendicular to the face of the end-effector and the x- and y-axes are parallel to its face [36]. The UFS is then attached to this face with its axes aligned with that of the tool system, $C_{tool.}$ Therefore, by translating the center of the tool coordinate system, the UFS or sensor coordinate system, C_{ufs} becomes identical to the robotic tool system.

Two additional coordinate systems are required before external loads can be applied theto the knee, and forces and moments can be measured. The last two coordinate systems define the location and position of the knee specimen and are the tibial and femoral coordinate systems (C_{tibia} and C_{femur}, respectively).

3.0 OBJECTIVES AND SPECIFIC AIMS

Overall Goals

Proper placement and fixation of each individual graft is important to avoid graft failure and a poor outcome. Using a 6 degree-of-freedom robotic/UFS testing system, it is possible to study a double bundle ACL reconstruction and compare its improved performance over the traditional single bundle procedure. Data such as knee kinematics, the in situ force of the ACL and its bundles, as well as in the ACL replacement grafts can be determined for various double bundle procedures. This information will be used to understand how changing specific parameters such as, the knee flexion angle at which the grafts are fixed, affects the two grafts in double bundle ACL reconstruction. Therefore, the ***overall goal*** of this thesis project is to determine how fixation of the grafts at various knee flexion angles affects the biomechanical outcome of a double bundle ACL reconstruction. The ***overall hypothesis*** is that a double bundle procedure can restore knee stability in terms of knee kinematics and in situ forces, however, the way the grafts are fixed will affect both of these parameters, in terms of how closely the grafts function compared to the intact bundles. This study is an important step towards the understanding of the tensioning pattern of the two grafts in DB-ACLR based on specific changes attributed to how the grafts are fixed.

Specific Aim 1: **To determine if and how the knee flexion angle for graft fixation has an effect on the force distribution of ACL grafts.** There exists a countless combination of knee flexion angles for the fixation of the two grafts in double bundle ACL reconstruction. According to the literature, the range of knee flexion angles used by surgeons varies widely, i.e. from 10° to 90° for the AM graft and from full extension to 60° for the PL graft. Some authors have advocated fixation of the two grafts at one knee flexion angle, while other authors have recommended graft fixation at different knee flexion angles for each graft that correspond to those used in laboratory studies [16, 17]. Therefore, two fixation protocols, based on each of the schools of thought will be utilized in order to determine if the change of knee flexion angle for graft fixation, has any affect in the force distribution of the two grafts. Since some authors believe that both grafts should be fixed at the same knee flexion angle, for the first fixation protocol, 30° of knee flexion will be chosen for the fixation of both the AM and PL graft. The second belief is that, the grafts should be fixed at knee flexion angles at which their respective intact bundles carries higher loads. Therefore, for the second fixation protocol, the AM graft will be fixed at 60° of knee flexion, while the PL graft will be fixed at full extension.

Hypothesis 1: Since it is known that the PL bundle starts out taut at extension, and becomes lax beyond 30° of knee flexion, while the AM bundle has some tension at extension and increases in tautness as the knee flexes, it is hypothesized that the fixation of the PL graft at 30° of knee flexion will overload it as it approaches extension.

<u>Specific Aim 2:</u> **Determine a range of flexion angles for AM graft fixation, that will not overload either graft in DB-ACLR.** Based on the findings of Specific Aim 1, a narrower range of knee flexion angles is being sought for both grafts. It is understood that an elevated or imbalanced force distribution between the AM and PL grafts could predispose one or both of the graft to failure. The results of Specific Aim 1, in combination with other studies, suggests that the range of knee flexion angles that are safe for the fixation of the PL graft is small, whereas the range of knee flexion angles for the AM graft may be larger. Because there are a variety of factors, including graft choice, initial graft tensioning, fixation method, etc… that can all affect the outcome, only a range of knee flexion angles is being sought.

<u>Hypothesis 2:</u> It is believed that, by holding the PL graft at one flexion angle near extension (i.e. 15°), a range of knee flexion angles can be found that will be safe for the fixation of both grafts.

<u>Specific Aim 3:</u> **Evaluate the biomechanical outcome of a double bundle procedure with only a single femoral tunnel and compare to the fixation protocol identified as the most similar to the intact knee in Specific Aim 2.** Double bundle reconstruction offers the advantage of reconstructing both the bundles of the ACL, which laboratory studies have shown to play a significant role in maintaining knee stability. However, most protocols call for the drilling of two femoral tunnels, as well as one to two tibial tunnels, which could become problematic in the event of a revision surgery. Clinical outcome studies have shown that the primary cause for ACL graft failure in single bundle procedures is due to improper tunnel placement [31, 32]. Therefore, the drilling and positioning of two tunnels may cause even more

problems for surgeons. It has unfortunately been well documented, that the rate of success for revision ACL reconstruction is poor. Therefore, a method is being studied in which the two bundles will be replicated with only a single femoral tunnel required for the PL graft, by placing the AM graft over the top of the lateral femoral epicondyle [25]. An over the top graft technique has typically been used for a single bundle reconstruction with success, since its positioning in the knee joint and function are similar to the AM bundle [38]. The addition of the PL graft, via a femoral tunnel, then provides a two graft complex.

Hypothesis 3: The overall biomechanical performance of a DB-ACLR procedure with a single femoral tunnel should be comparable to a DB-ACLR procedure chosen from Specific Aim 2, since the position of the two grafts will be similar to the DB-ACLR procedure with two femoral tunnels.

4.0 METHODS

Human cadaveric knees will be tested for this study based on a power analysis. Roentgenograms of specimens will be taken and examined to ensure there is no evidence of osteoarthritis and bony abnormalities. Specimens are to be stored in airtight plastic bags at -20°C until 24 hours before testing when they will be thawed at room temperature [39, 40]. Arthroscopic examination of the knee joint will be performed to confirm the presence of an intact and functional ACL.

The semitendinosus and gracilis tendons were chosen as ACL replacement grafts, which will be harvested using a tendon stripper from each knee through an approximately 4 cm long longitudinal incision on the anteromedial portion of the proximal tibia, 2 cm distal to the tibial tuberosity. The grafts will then be wrapped in saline-soaked gauze to prevent dehydration.

In preparation for testing, all soft tissue will be removed approximately 10 cm away from the joint line on both the femur and the tibia, while leaving the knee joint intact [41]. The fibula will be fixed to the tibia with a metal screw to maintain its anatomic position. The tibia and the femur will each be secured within custom made aluminum cylinders by using an epoxy compound (Fibre Glass-Evercoat, Cincinnati, Ohio) with transfixing bolts. The specimen is to then be mounted in a robotic universal force moment sensor (UFS) testing system. The femoral side will be rigidly mounted to the base of the robotic manipulator (PUMA Model 726; Unimate

Inc, Danbury, CT), while the tibial side will be attached to the end-effector of the robotic manipulator via a load cell (Model 4015; JR3 Inc, Woodland, CA).

4.1. SURGICAL PROCEDURE FOR SPECIFIC AIM 1

DB-ACLR will be performed using two femoral tunnels and a single tibial tunnel using a medial arthrotomy to better visualize the insertions of the individual bundles of the ACL. The medial arthrotomy will be done during specimens preparation, therefore, any effect of performing this procedure will be consistent throughout the experiment. Femoral tunnels are to be drilled on the footprints of the two bundles, which corresponded roughly to around 11:00 o'clock for the AM graft and around 9:00 o'clock for the PL graft for a right knee and 1:00 o'clock and 3:00 o'clock, respectively, for a left knee. The diameter of the femoral tunnels for the AM and PL grafts will be chosen according the graft size (range 6-8 mm for AM) and (range 5-7 mm for PL). Both the AM and PL femoral tunnels will be positioned using a Kirschner wire at the center of the insertion of each bundle of the ACL by visual inspection of the remnants of the transected bundles. The femoral tunnels will first be drilled 30 mm deep inside the joint using a cannulated drill bit chosen according to the graft diameter; then the tunnels will be drilled through with a 4.5 mm diameter cannulated drill (EndoButton Drill, Acufex, Smith & Nephew, Andover, Mass). A single tibial tunnel is to be placed using a Protac tibial guide set at 55˚. The diameter of the tibial tunnel should be equal to the diameter of the AM and PL combined graft (range 7.5-10 mm). Looped semitendinosus tendon and gracilis tendon will be used for the AM and the PL grafts, respectively. For each graft, the femoral side will be fixed first using an

EndoButton® CL. The grafts will then be pulled through the tibial tunnel and the knee will be preconditioned by moving the knee through 5 cycles of the full range of knee flexion while applying a 22 N pretension to each graft. Finally, the tibial side will be fixed using two spiked washers and two screws. For fixation protocol 30/30, both grafts will be fixed at the same knee flexion angle of 30°, while for fixation protocol 60/FE, the AM graft will be fixed at 60° of knee flexion and the PL graft at full extension (Figure 4). Each graft will be fixed while a 67 N posterior tibial load and 22 N of initial graft tension is maintained. Previous studies have shown

that applying 67 N of posterior load during the fixation of the grafts can more closely restore the knee kinematics and the *in situ* force in the ACL graft to those of the intact knee [28, 42]. The initial graft tension was chosen according to a previous publication which determined that 44 N was enough to restore the knee kinematics without over constraining the knee joint. Therefore, 22 N of initial graft tension will be applied to each graft, which totals in 44 N of initial graft tension. The order of graft fixation will be randomized among knees.

Once the knee is prepared and mounted on the robotic/UFS testing system, a passive path

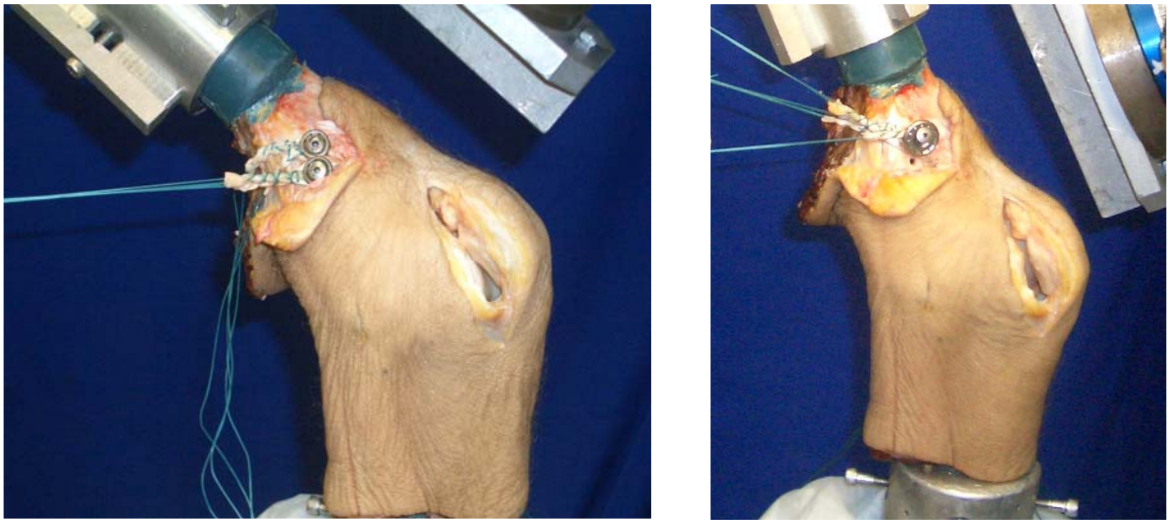

Figure 4. (A) Fixation 60/FE: AM graft fixed at 60° and PL graft fixed at full extension. (B) Fixation 30/30: Both grafts fixed at 30° of knee flexion

of flexion/extension will be found in order to establish a reference path from which kinematics data can be determined. The knee is mounted at full extension, and the path of passive flexion/extension is fund from full extension to 90° of knee flexion in 1° increments by means of minimizing all the external forces and moments. Once our reference path has been found, two external loading conditions will be applied to the knee. The first consists of a 134-N anterior tibial load (ATL) applied with the knee in full extension, 15°, 30°, 60°, and 90° of knee flexion. The ATL simulates clinical exams such as the anterior drawer and the Lachman tests, which are commonly used to diagnose ACL deficiency. The second loading condition will consist of a combined 10 N-m valgus torque and a 5 N-m internal/external tibial torque applied at 15° and 30° of knee flexion. The combined rotatory load (CRL) statically simulates the pivot shift test, which is another exam used to determine knee instability, as well as to evaluate the effectiveness of restoring knee stability, especially rotatory stability of an ACL reconstruction procedure.

4.2 PROTOCOL FOR SPECIFIC AIM 2

The goal of Specific Aim 2 is to determine a safe range of knee flexion angles for graft fixation, so as not to overload either of the grafts in DB-ACLR. The findings of specific aim 1 served as a guideline for the fixation protocols. Therefore, the specimen preparation, and experimental protocol are nearly the same as in Specific Aim 1. The difference is in the two new fixation protocols being tested. The grafts will once again be pulled through the tibial tunnel and the knee will be preconditioned by moving the knee through 5 cycles of the full range of knee flexion while applying a 22 N pretension to each graft. The tibial side will be fixed using two spiked washers and two screws. For fixation protocol 15/15, both grafts will be fixed at the same knee flexion angle of 15°, while for fixation protocol 45/15, the AM graft will be fixed at 45° of knee flexion and the PL graft at 15°. Each graft will be fixed while a 67 N posterior tibial load and 22 N of initial graft tension is maintained.

Once the knee is prepared and mounted on the robotic/UFS testing system, a passive path of flexion/extension will be found from full extension to 120° of knee flexion. Once our reference path has been found, the same two external loading conditions will be applied to the knees as was done in Specific Aim 1. The first consists of a 134-N anterior tibial load (ATL) applied with the knee in full extension, 15°, 30°, 45°, and 90°, and 120° of knee flexion. The second loading condition will consist of a combined 10 N-m valgus torque and a 5 N-m internal/external tibial torque applied at 15° and 30° of knee flexion.

4.3 SURGICAL PROTOCOL FOR SPECIFIC AIM 3

The goal of Specific Aim 3 is to investigate whether a double bundle procedure with only one femoral tunnel, is biomechanically similar to the intact knee, as well as another double bundle procedure with two femoral tunnels. The results from specific Aim 2 are being used to determine a double bundle protocol with two femoral tunnels to compare against a procedure that has only one femoral tunnel. Therefore the two fixation protocols being tested are fixation protocols 45/15 and PL+OTT.

The knee specimens will still be prepared in the same manner as in Specific Aims 1 and 2. Looped semitendinosus and gracilis tendons will be used for the OTT and the PL grafts, respectively. The looped ends will be fixed on the femur whereas sutured ends will be fixed on the tibia for both grafts. For the femoral fixation, for the OTT graft, a small incision will be made over the lateral epicondyle and the bone will be exposed. Then, the graft will be passed over-the-top, and fixed on the lateral epicondyle using a staple between the two legs of the looped tendon so as to provide a secure fixation. Femoral fixation of the PL graft will be done using an endobutton-CL. A 20 mm (Figure 5) tunnel will be drilled on the PL bundle insertion site according to the size of the looped gracilis graft (~5-7 mm). Then the tunnel will be extended to the cortex using an endobutton drill (4.5 mm) in order to pass the endobutton-CL. The sutured ends of the both grafts will be passed through the full length tibial tunnel which will be drilled on the posterior aspect of the ACL insertion site according to the size of the two grafts (~8-10 mm) using a tibial guide (previous papers). After passing the grafts, the knee will be manually flexed and extended to precondition the grafts for 10 cycles. Finally, the OTT graft will be fixed at 45 degrees of knee flexion, whereas the PL graft will be fixed at 15 degrees of knee flexion under 22 N tension. During fixation, a 67 N posterior load will applied to the tibia, because this loading condition has been shown to reproduce the knee kinematics closer to the intact knee.

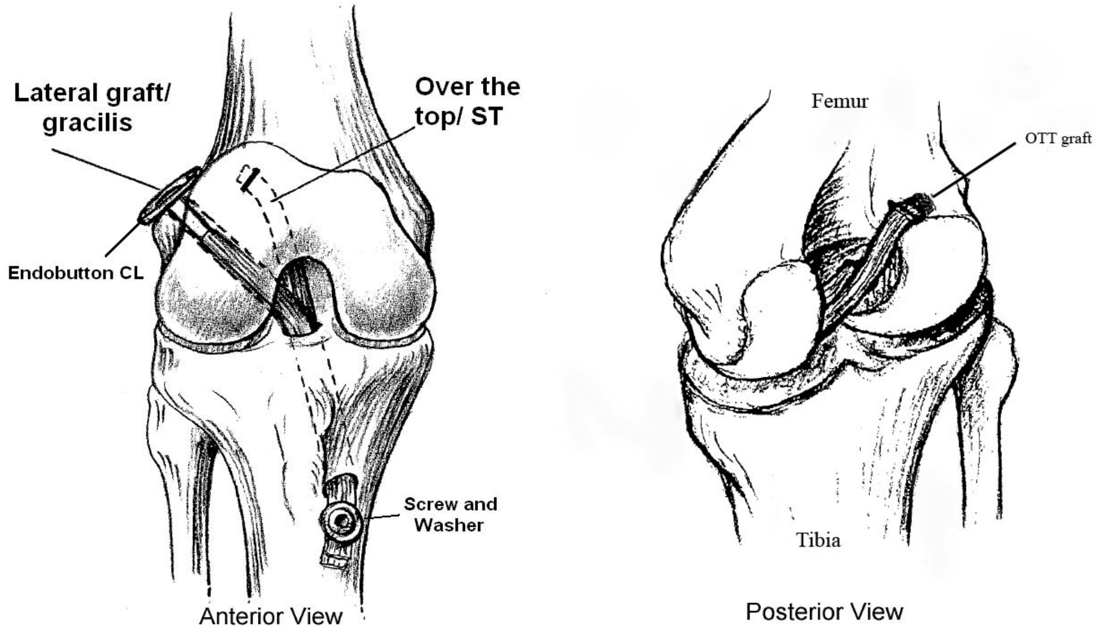

Figure 5. (A) Anterior view of PL+OTT technique (B) Posterior view of PL+OTT technique

Once the knee is prepared and mounted on the robotic/UFS testing system, a passive path of flexion/extension will be found from full extension to 90° of knee flexion. After the reference path has been found, the same two external loading conditions will be applied to the knees as was done in Specific Aims 1 and 2. The first consists of a 134-N anterior tibial load (ATL) applied with the knee in full extension, 15°, 30°, 45°, and 90° of knee flexion. The second loading condition will consist of a combined 10 N-m valgus torque and a 5 N-m internal/external tibial torque applied at 15° and 30° of knee flexion.

4.4 STATISTICAL METHODS

Based on our previous data, a power analysis will be performed (power = 0.80, significance level = 0.05), so differences of 3 mm for anterior tibial translation (ATT) and 20 N for *in situ* force measurements can be detected for each Specific Aim. Because all variables will be measured on the same specimen, statistical analysis of the ATT, and *in situ* forces will be performed using a 1-factor repeated measures analysis of variance, with knee state as the factor. This analysis has the advantage of being sensitive to relative changes occurring within an individual knee and minimizing the effects of interspecimen variability. Therefore, a large number of specimens (>20) will not be required in order to find statistically significant differences. A Bonferroni adjustment will be done to evaluate the effects of ACL reconstruction at specific angles of knee flexion. Statistical significance will be set at $p < 0.05$. According to each power analysis, 10 specimens were required for Specific Aim 1, 9 specimens for Specific Aim 2, and 10 specimens for Specific Aim 3.

5.0 RESULTS

In this section, the results from the experimental tests from each Specific Aim are presented. The overall knee kinematics for the intact, ACL-deficient, as well as reconstructed states will be presented, in response to both loading conditions. The in situ force of the intact ACL, and combined ACL grafts, as well as the intact bundles and their respective replacement grafts will also be presented. The results will be presented in order of the specific aims.

5.1 SPECIFIC AIM 1

Anterior Tibial Load

Under a 134 N anterior tibial load, the anterior tibial translation of the intact knee ranged from 4.1 ± 2.2 mm at full extension to 8.3 ± 2.1 mm at 30˚ of knee flexion (Table 1).

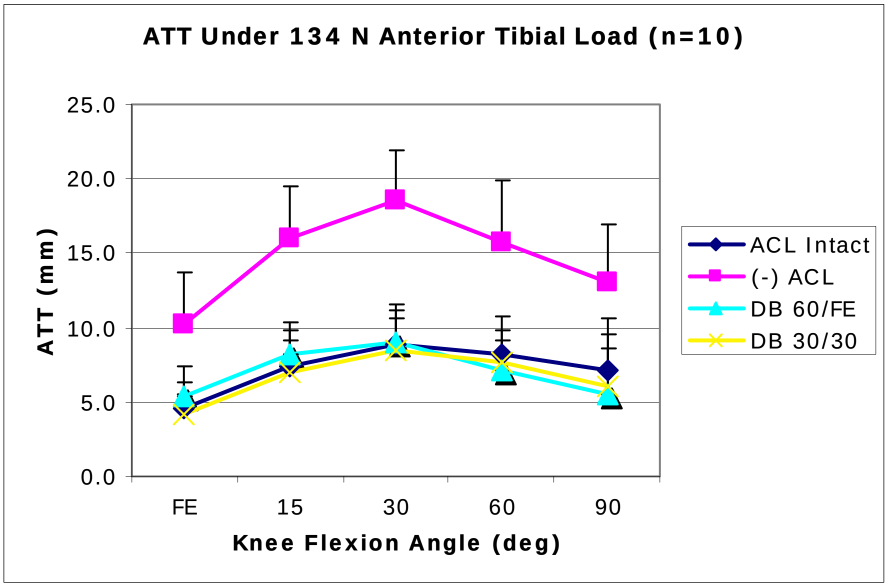

Figure 6. ATT Under 134 N Anterior Tibial Load

After the ACL was transected, the ATT more than doubled for all the flexion angles tested, measuring as high as 18.0 ± 4.0 mm at 30° ($p<0.05$). Following ACL reconstruction, the ATT was restored to within 1.7 mm of the intact knee for both fixation protocols 30/30 and 60/FE (Table 2). For example, the ATT at 30˚ of knee flexion, was 8.5 ± 3.6 mm for fixation protocol 30/30 and 9.0 ± 3.6 mm for fixation protocol 60/Fe. Although, the maximum anterior laxity was only 1.7 mm, statistically significant differences were found between fixation protocol 60/FE and the intact knee.

Table 1. Anterior tibial translation (mm) under 134 N ATL

Angle	Anterior Tibial Translation (mean ± StDev)			
(degrees)	Intact	ACL(-)	30/30	60/FE
FE	4.5 ± 2.0	10.2 ± 4.1*	4.2 ± 3.6	5.4 ± 3.7
15	7.5 ± 2.1	16.0 ± 4.6*	7.0 ± 3.7	8.2 ± 3.8
30	8.8 ± 3.0	18.6 ± 3.8*	8.5 ± 3.6	9.0 ± 3.6
60	8.2 ± 2.9	15.7 ± 4.5*	7.7 ± 2.9	7.2 ± 2.4
90	7.1 ± 2.9	13.1 ± 4.0*	6.1 ± 2.8*	5.5 ± 2.5*

* indicates statistical differences vs. the intact knee

Shown in Table 2 are the overall *in situ* forces of the intact ACL and the AM and PL bundles as well as the AM and PL grafts for both fixation protocols 30/30 and 60/FE. In response to the 134 N ATL, the *in situ* force in the intact ACL ranged from 74 ± 16 N at 90˚ to 113 ± 17 N at 30˚. For fixation protocol 30/30 the corresponding value for the combined grafts were 74 ± 22 N to 107 ± 18 N and were not statistically different compared to the intact knee ($p>0.05$). For fixation protocol 60/FE, the *in situ* force for the combined ACL grafts ranged from 79± 21 to 106 ± 22 at 90˚ and 30˚ of knee flexion, respectively, and were not different from those of the intact ACL ($p>0.05$). Further, no statistical differences were found between the two fixation protocols i.e. 30/30 vs. 60/FE, except at full extension ($p < 0.05$).

Table 2. In situ force (N) of ACL and grafts under 134 N ATL

Angle	**ACL In Situ Force (mean ± StDev)**		
(degrees)	**Intact**	**30/30**	**60/FE**
FE	88 ± 32	104 ± 22	81 ± 26
15	110 ± 25	114 ± 18	106 ± 23
30	113 ± 17	107 ± 18	106 ± 22
60	90 ± 18	83 ± 27	91 ± 20
90	74 ± 16	74 ± 22	79 ± 21

* indicates statistical differences vs. the intact ACL

Results for the *in situ* force in the AM and PL bundles and their respective individual grafts were also obtained and compared. For the intact AM bundle, they ranged from 43 ± 17 N at full extension to 82 ± 17 N at 60˚ in response to the 134 N anterior tibial load (Table 3). The corresponding values for the AM graft in each fixation protocol were 43 ± 18 N at full extension to 65 ± 23 N at 60˚ for fixation protocol 30/30, and 48 ± 20 N to 89 ± 19 N for fixation protocol 60/FE, respectively. Compared to the intact knee, the *in situ* forces for fixation protocol 30/30 were 71.2% and 78.7% of the intact AM bundle values at 30˚ and 60˚ of knee flexion, respectively. Conversely, the AM graft for fixation protocol 60/FE were significantly higher than the intact AM bundle at 15˚ and 30˚ of knee flexion ($p < 0.05$). When comparing the two fixation protocols with each other, the *in situ* forces in the AM graft for fixation protocol 30/30 were significantly lower than those for fixation protocol 60/FE, from 15° to 90°of knee flexion.

Table 3. In situ force (N) of AM bundle/graft under 134 N ATL

Angle	**AM In Situ Force (mean ± StDev)**		
(degrees)	**Intact**	**30/30**	**60/FE**
FE	43 ± 18	43 ± 18	48 ± 19
15	54 ± 15	41 ± 14	76 ± 21***†**
30	71 ± 15	50 ± 17*****	90 ± 21***†**
60	82 ± 17	65 ± 23*****	89 ± 19**†**
90	72 ± 16	64 ± 20	84 ± 24**†**

*indicates statistical differences vs. intact AM bundle
†indicates statistical differences between fixation protocols 30/30 vs. 60/FE

The *in situ* forces in the intact PL bundle ranged from 57 ± 37 N at 15˚ to 7 ± 4 N at 90˚ of knee flexion. Those for the PL graft ranged from 77 ± 18 N at 15˚ to 10 ± 8 N at 90˚ of knee flexion for fixation protocol 30/30, and from 30 ± 13 N to 2 ± 2 N for fixation protocol 60/FE, respectively (Table 4). The in situ force in the PL graft was significantly higher than the PL bundle for fixation protocol 30/30 at 15˚ and 30˚ of knee flexion ($p<0.05$). In contrast, the in situ force of the PL graft for fixation protocol 60/FE was significantly lower than the intact PL bundle at 15˚ and 30˚ of knee flexion. When comparing the two fixation protocols, the in situ forces in the PL graft for fixation protocol 30/30 were significantly higher than for fixation protocol 60/FE throughout the range of flexion, except at 90˚ ($p<0.05$).

Table 4. In situ force (N) of PL bundle/graft under 134 N ATL

Angle	**PL In Situ Force (mean ± StDev)**		
(degrees)	**Intact**	**30/30**	**60/FE**
FE	43 ± 18	48 ± 19	43 ± 18†
15	54 ± 15	76 ± 21*	41 ± 14*†
30	71 ± 15	90 ± 21*	50 ± 17*†
60	82 ± 17	89 ± 19	65 ± 23†
90	72 ± 16	84 ± 24	64 ± 20

*indicates statistical differences vs. intact PL bundle
†indicates statistical differences between fixation protocols 30/30 vs. 60/FE

Combined Rotatory Loads

Under the combined rotatory loads, the coupled anterior tibial translation of the intact knee was 4.7 ± 2.7 mm at 15˚ and 7.0 ± 3.0 mm at 30˚ of knee flexion while the internal tibial rotation (ITR) was 13.8 ± 5.2˚ and 17.9 ± 6.0˚, respectively (Table 5). After transection of the ACL, the coupled ATT values increased significantly to 10.1 ± 4.5 mm and 11.9 ± 3.6 mm at 15° and 30° respectively ($p<0.05$). Following ACL reconstruction with fixation protocol 30/30, the coupled ATT was 4.5 ± 4.7 mm at 15˚ and 6.0 ± 3.9 mm at 30˚, while the ITR was 11.6 ± 9.6˚, and 14.5 ± 9.6˚, respectively and were statistically higher than that of the intact knee. Results obtained for fixation protocol 60/FE for the coupled ATT were 5.8 ± 4.7 mm at 15˚ and 7.5 ± 4.0 mm at 30˚, while the ITR was 14.4 ± 4.8˚, and 18.7 ± 5.6˚. Both fixation protocols significantly reduced the coupled ATT compared to the ACL-deficient knee, although fixation protocol 30/30 showed a tendency to constrain the knee, while fixation protocol 60/FE was generally more lax than the intact knee ($p<0.05$).

Table 5. Anterior tibial translation (mm) under combined rotatory loads

Angle	**Coupled ATT (mean ± StDev)**			
(degrees)	**Intact**	**ACL(-)**	**30/30**	**60/FE**
15	5.1 ± 2.4	10.1 ± 4.5*****	4.6 ± 4.7	6.1 ± 4.6**†**
30	7.6 ± 2.7	12.2 ± 3.7*****	6.4 ± 4.1	8.1 ± 3.9**†**

*indicates statistical differences vs. intact knee
†indicates statistical differences between fixation protocols 30/30 vs. 60/FE

Under CRL, the *in situ* force of the intact ACL was 80 ± 15 N at 15˚ and 68 ± 27 N at 30˚ of knee flexion. The corresponding values for fixation protocol 30/30 were 82 ± 19 N and 80 ± 18 N, while for fixation protocol 60/FE the values were 71 ± 17 N and 67 ± 19 N, respectively. As in the case of the applied ATL, no statistically significant differences were found between the *in situ* force of the ACL grafts for both the fixation protocols and the intact ACL.

Results for the *in situ* force in the intact AM and PL bundles and their respective individual grafts were also obtained and compared. The *in situ* force in the intact AM bundle was 42 ± 13 N at 15˚ and 42 ± 15 N at 30˚ of knee flexion. The corresponding values for the AM graft for fixation protocol 30/30, were 26 ± 13 N at 15˚ and 30 ± 15 N at 30˚ of knee flexion, while for fixation protocol 60/FE they were 46 ± 11 N at 15˚ and 41 ± 17 N at 30˚ of knee flexion (Table 6). As in the case of the applied ATL, the *in situ* force in the AM graft for fixation protocol 30/30 was on average 35% lower than that of the intact AM bundle ($p<0.05$). No statistical difference was found between the AM graft for fixation protocol 60/FE and the intact AM bundle at either of the flexion angles tested. The *in situ* forces in the intact PL bundle were 39 ± 19 N at 15˚ and 26 ± 17 N at 30˚ of knee flexion. The corresponding values for the PL graft for fixation protocol 30/30 were 57 ± 21 N at 15˚ and 51 ± 14 N at 30˚ of knee flexion, while for fixation protocol 60/FE they were 25 ± 13 N and 27 ± 14 N, respectively (Table 6). The in situ force for the PL graft of fixation protocol 30/30 was significantly higher than that of the intact PL bundle at both flexion angles tested. When comparing the two fixation protocols, the in situ force of the PL graft for fixation protocol was significantly higher than the PL graft for fixation protocol 60/FE at both flexion angles ($p<0.05$).

Table 6. In situ force (N) of bundles/grafts under combined rotatory loads

Angle	**AM In Situ Force (mean ± StDev)**			**PL In Situ Force (mean ± StDev)**		
(degrees)	**Intact AM**	**30/30**	**60/FE**	**Intact PL**	**30/30**	**60/FE**
15	42 ± 13	26 ± 14*****	47 ± 12**†**	39 ± 19	57 ± 21*****	25 ± 13**†**
30	42 ± 16	27 ± 17*****	41 ± 18**†**	26 ± 17	51 ± 14*****	27 ± 14**†**

*indicates statistical differences vs. intact bundle
†indicates statistical differences between fixation protocols 30/30 vs. 60/FE

As seen from the data presented, the *in situ* forces for the AM and PL bundles were not always similar to that of their respective intact bundle. Table 6 illustrates that under an applied 134 N anterior tibial load, the AM graft for fixation protocol 30/30 generally carried lower load than the intact AM bundle, while the AM graft for fixation protocol 60/FE carried higher loads. Conversely, the PL graft for fixation protocol 30/30 carried significantly higher loads than the intact PL bundle at two flexion angles, where as the PL graft for fixation protocol 60/FE was significantly lower than the intact bundle. Furthermore, Table 6, shown above also demonstrates a similar trend among the grafts under the combined rotatory loads.

Therefore, based on the force distribution of the two grafts, it seems that the AM graft should be fixed at a flexion angle that is less than 60° of knee flexion, because the AM graft for fixation protocol 60/FE carries higher loads than the intact AM bundle under the anterior tibial load. For the PL graft, it appears that the graft should be fixed somewhere between full extension and 30° of knee flexion, since with fixation protocol 30/30 the PL graft carries significantly higher loads, while the PL graft for fixation protocol 60/FE carries significantly less loads at the same knee flexion angles. These results are going to be used in order to choose two new fixation protocols which will narrow the range of flexion angles used for graft fixation. Therefore, for the second Specific Aim, the AM graft should be fixed within a range that is less than 60° of knee flexion, while the PL graft should be fixed around 15° of knee flexion [43].

5.2 SPECIFIC AIM 2

Anterior Tibial Load

Under a 134 N anterior tibial load, the anterior tibial translation of the intact knee ranged from 4.0 ± 0.9 mm at full extension to 7.6 ± 2.1 mm at 30˚ of knee flexion (Table 7).

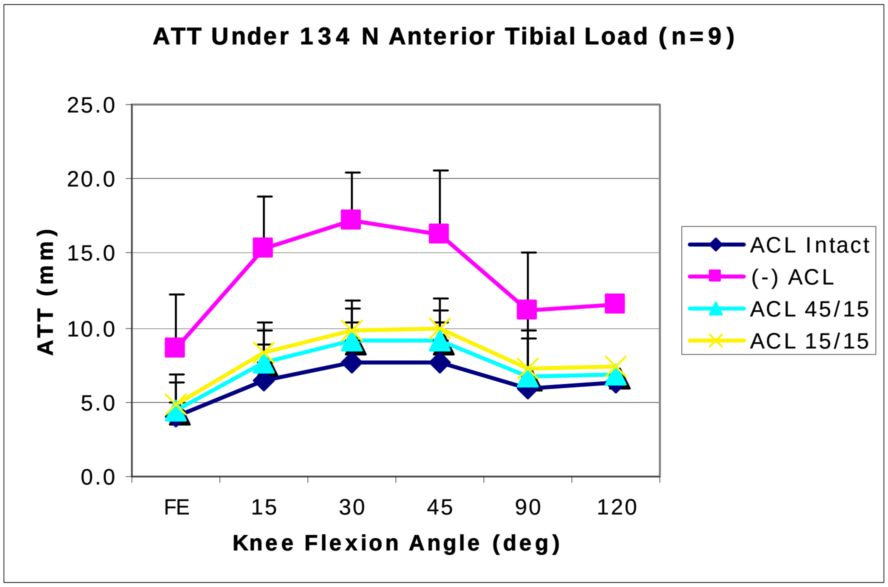

Figure 7. ATT Under 134 N Anterior Tibial Load

After the ACL was transected, the ATT more than doubled for all the flexion angles tested, measuring as high as 17.2 ± 3.0 mm at 30° ($p<0.05$). Following ACL reconstruction, the ATT was restored to within 2.2 mm of the intact knee for both fixation protocols 15/15 and 45/15 (Table 7). For example, the ATT at 30˚ of knee flexion, was 9.8 ± 2.1 mm for fixation protocol 15/15 and 9.1 ± 2.4 mm for fixation protocol 45/15. Although, the maximum anterior laxity was only 2.2 mm, statistically significant differences were found between fixation protocol 15/15 and the intact knee.

Table 7. Anterior tibial translation (mm) under 134 N ATL

Angle	**Anterior Tibial Translation (mean ± StDev)**			
(degrees)	**Intact**	**ACL(-)**	**15/15**	**45/15**
FE	4.0 ± 0.9	8.6 ± 2.1*	4.8 ± 1.4	4.4 ± 1.4
15	6.5 ± 1.6	15.3 ± 2.4*	8.3 ± 2.0*	7.7 ± 2.1
30	7.6 ± 2.1	17.2 ± 3.0*	9.8 ± 2.1*	9.1 ± 2.4
45	7.7 ± 2.2	16.3 ± 3.7*	9.9 ± 1.9*	9.2 ± 2.1
90	5.9 ± 2.1	11.1 ± 3.5*	7.3 ± 1.8*	6.7 ± 1.8
120	6.3 ± 1.9	11.6 ± 2.7*	7.4 ± 1.9	6.8 ± 1.7

*indicates statistical differences vs. intact knee

Shown in Table 8 are the overall *in situ* forces of the intact ACL and the AM and PL bundles as well as the AM and PL grafts for both fixation protocols 15/15 and 45/15. In response to the 134 N ATL, the *in situ* force in the intact ACL ranged from 76 ± 14 N at 120˚ to 119 ± 20 N at 15˚. For fixation protocol 15/15 the corresponding value for the combined grafts were 63 ± 18 N to 107 ± 16 N and were not statistically different compared to the intact knee (p>0.05). Similarly, for fixation protocol 45/15, the *in situ* force for the combined ACL grafts was also not different from those of the intact ACL (p>0.05). Further, no statistical differences were found between the two fixation protocols i.e. 15/15 vs. 45/15, (p >0.05).

Table 8. In situ force (N) of ACL/grafts under 134 N ATL

Angle	**ACL In Situ Force (mean ± StDev)**		
(degrees)	**Intact**	**15/15**	**45/15**
FE	87 ± 23	73 ± 24	82 ± 28
15	119 ± 20	107 ± 16	111 ± 15
30	116 ± 14	103 ± 22	109 ± 17
45	103 ± 15	86 ± 21*****	93 ± 18
90	79 ± 14	62 ± 18	70 ± 24
120	76 ± 14	63 ± 18	66 ± 18

*indicates statistical differences vs. intact ACL

Results for the *in situ* force in the AM and PL bundles and their respective individual grafts were also obtained and compared. For the intact AM bundle, they ranged from 46 ± 25 N at full extension to 79 ± 21 N at 45˚ in response to the 134 N anterior tibial load (Table 9). The corresponding values for the AM graft in each fixation protocol were 31 ± 16N at full extension to 61 ± 20 N at 45˚ for fixation protocol 15/15, and 45 ± 26 N to 73 ± 17 N for fixation protocol 45/15, respectively (p>0.05). Compared to the intact knee, the *in situ* forces for fixation protocol 15/15 were 79.3% and 77.9% of the intact AM bundle values at 30˚ and 45˚ of knee flexion, respectively. When comparing the two fixation protocols with each other, the *in situ* forces in the AM graft for fixation protocol 15/15 were significantly lower than those for fixation protocol 45/15, at 30° and 45°of knee flexion.

Table 9. In situ force (N) of AM bundle/graft under 134 N ATL

Angle	**AM In Situ Force (mean ± StDev)**		
(degrees)	**Intact**	**15/15**	**45/15**
FE	46 ± 25	31 ± 16	45 ± 26
15	63 ± 37	52 ± 22	60 ± 26
30	77 ± 27	61 ± 17*****	74 ± 25
45	79 ± 21	61 ± 20*****	73 ± 17†
90	68 ± 13	49 ± 19*****	59 ± 24
120	57 ± 17	41 ± 16	43 ± 16

*indicates statistical differences vs. intact AM bundle
†indicates statistical differences between fixation protocols 15/15 vs. 45/15

The *in situ* forces in the intact PL bundle ranged from 57 ± 37 N at 15˚ to 13 ± 11 N at 90˚ of knee flexion. Those for the PL graft ranged from 55 ± 20 N at 15˚ to 12 ± 9 N at 90˚ of knee flexion for fixation protocol 15/15, and from 52 ± 15 N to 12 ± 11 N for fixation protocol 45/15, respectively (Table 10). There was no statistically significant difference between the PL grafts for both fixation protocols with those for the intact PL bundle ($p>0.05$). Also, there was no difference in between the grafts of the two fixation protocols from full extension to full flexion ($p>0.05$).

Table 10. In situ force (N) of PL bundle/graft under 134 N ATL

Angle	PL In Situ Force (mean ± StDev)		
(degrees)	**Intact**	**15/15**	**45/15**
FE	43 ± 21	48 ± 21	38 ± 11
15	57 ± 36	55 ± 20	52 ± 15
30	39 ± 26	44 ± 11	35 ± 12
45	25 ± 20	24 ± 6	21 ± 8
90	13 ± 11	12 ± 9	12 ± 11
120	21 ± 21	26 ± 15	25 ± 17

Combined Rotatory Loads

Under the combined rotatory loads, the coupled anterior tibial translation of the intact knee was 4.5 ± 3.7 mm at 15˚ and 6.3 ± 4.1 mm at 30˚ of knee flexion while the internal tibial rotation (ITR) was 15.1 ± 3.4˚ and 17.2 ± 3.6˚, respectively (Table 11). After transection of the ACL, the ATT values increased significantly to 10.1 ± 4.8 mm and 10.9 ± 4.8 mm at 15° and 30° respectively ($p<0.05$). Following ACL reconstruction with fixation protocol 15/15, the ATT was 6.1 ± 4.2 mm at 15˚ and 7.7 ± 4.4 mm at 30˚, while the ITR was 16.8±3.1˚, and 18.5±3.3˚, respectively and were statistically higher than that of the intact knee. Results obtained for fixation protocol 45/15 were comparable to the intact knee as there were no significant changes in ATT (p>0.05).

Table 11. Anterior tibial translation (mm) under combined rotatory loads

Angle	**Coupled ATT (mean ± StDev)**			
(degrees)	**Intact**	**ACL(-)**	**15/15**	**45/15**
15	4.5 ± 3.7	10.1 ± 4.8*	6.1 ± 4.2*	5.7 ± 4.1
30	6.3 ± 4.1	10.9 ± 4.8*	7.7 ± 4.4*	7.4 ± 4.3

*indicates statistical differences vs. intact knee

Under CRL, the *in situ* force of the intact ACL was 82 ± 17 N at 15˚ and 70 ± 30 N at 30˚ of knee flexion. The corresponding values for fixation protocol 15/15 were 65 ± 24 N and 54 ± 30 N, while for fixation protocol 45/15 the values were 72 ± 19 N and 54 ± 22 N, respectively. As in the case of the applied ATL, no statistically significant differences were found between the *in situ* force of the ACL grafts for both the fixation protocols and the intact ACL.

Results for the *in situ* force in the intact AM and PL bundles and their respective individual grafts were also obtained and compared. The *in situ* force in the intact AM bundle was 41 ± 15 N at 15˚ and 41 ± 19 N at 30˚ of knee flexion. The corresponding values for the AM graft for fixation protocol 15/15, were 26 ± 11 N at 15˚ and 22 ± 13 N at 30˚ of knee flexion, while for fixation protocol 45/15 they were 39 ± 18 N at 15˚ and 29 ± 14 N at 30˚ of knee flexion (Table 12). As in the case of the applied ATL, the *in situ* force in the AM graft for fixation protocol 15/15 was 45% lower than that of the intact AM bundle at 30° of knee flexion (p<0.05). No statistical difference was found between the AM graft for fixation protocol 45/15 and the intact AM bundle at either of the flexion angles tested. The *in situ* forces in the intact PL bundle were 42 ± 22 N at 15˚ and 30 ± 18 N at 30˚ of knee flexion. The *in situ* force in the PL graft did not exceed those of the intact PL bundle for both fixation protocols. The corresponding values for the PL graft for fixation protocol 15/15 were 40 ± 17 N at 15° and 30 ± 15 N at 30° of knee flexion, while for fixation protocol 45/15 they were 37 ± 16 N and 26 ± 15 N, respectively (Table 12). There was no statistical difference between the two PL grafts and the intact PL bundle as well as in between the grafts of the two fixation protocols for both flexion angles tested, under the combined rotatory loads ($p>0.05$).

Table 12. In Situ force (N) of bundles/grafts under combined rotatory loads

Angle	**AM In Situ Force (mean ± StDev)**			**PL In Situ Force (mean ± StDev)**		
(degrees)	**Intact AM**	**15/15**	**45/15**	**Intact PL**	**15/15**	**45/15**
15	41 ± 15	26 ± 11	39 ± 18	42 ± 22	40 ± 17	37 ± 16
30	41 ± 19	22 ± 13*****	29 ± 14	30 ± 22	30 ± 15	26 ± 15

*indicates statistical differences vs. intact bundle

Both fixation protocols were able to restore knee kinematics to within clinically acceptable ranges of the intact knee. More importantly, neither fixation protocol 15/15 or 45/15 had in situ forces in the grafts higher than that of their respective intact bundles, as was the case for the fixation protocols studied in Specific Aim 1. The results of Specific Aim 2 also showed that fixation protocol 45/15, had both knee kinematics and in situ force in each of the grafts, closest to those of the intact knee. Although the differences found for fixation protocol 15/15 were within 2.2mm for knee kinematics, and within 20N for in situ force, statistically significant differences were determined for both parameters. In contrast, no statistical differences were found for either kinematics or in situ force for fixation protocol 45/15. Therefore, in the future, other double bundle ACL reconstructions should be compared to fixation protocol 45/15 in addition to the intact knee.

5.3 SPECIFIC AIM 3

Anterior Tibial Load

Under a 134 N anterior tibial load, the anterior tibial translation of the intact knee ranged from 3.7 ± 0.9 mm at full extension to 10.1 ± 2.6 mm at 45˚ of knee flexion (Table 13).

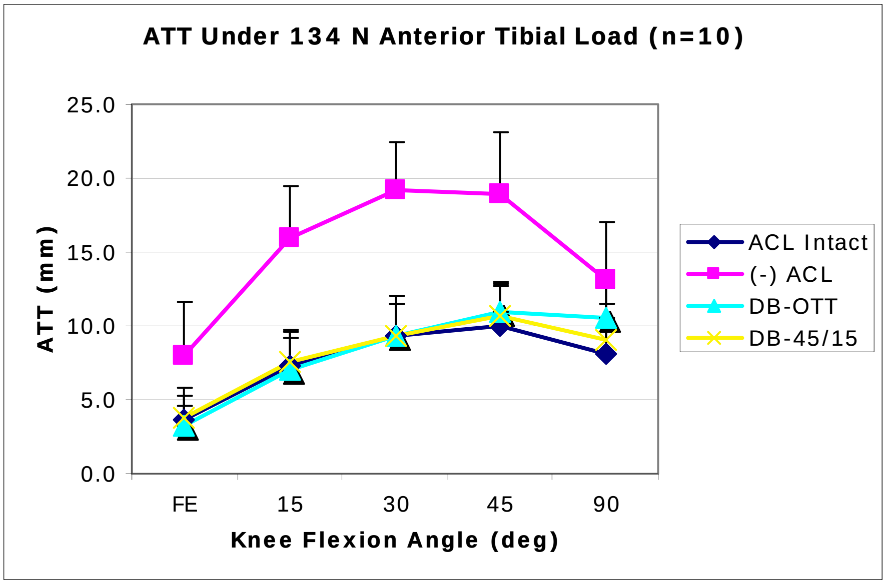

Figure 8. ATT Under 134 N Anterior Tibial Load

Following ACL reconstruction, the ATT was restored to within 1.0 mm of the intact knee for both fixation protocols 45/15 and PL+OTT, except at 90˚ of knee flexion where, the PL+OTT procedure showed greater laxity (Table 13). For example, the ATT at 45˚ of knee flexion, was 10.7 ± 2.0 mm for fixation protocol 45/15 and 11.0 ± 2.1 mm for fixation protocol PL+OTT. The anterior tibial translation for fixation protocol PL+OTT was significantly higher than that of the intact knee at 90˚ of knee flexion ($p<0.05$). No statistically significant differences in ATT were found between the two fixation protocols.

Table 13. Anterior tibial translation (mm) under 134 N ATL

Angle	Anterior Tibial Translation (mean ± StDev)			
(degrees)	Intact	ACL(-)	45/15	PL+OTT
FE	3.7 ± 0.9	8.0 ± 3.6*	3.8 ± 2.1	3.3 ± 2.1
15	7.4 ± 2.3	16.0 ± 3.5*	7.1 ± 2.1	7.1 ± 2.1
30	9.4 ± 2.7	19.2 ± 3.2*	9.4 ± 2.1	9.3 ± 2.1
45	10.1 ± 2.6	18.9 ± 4.2*	10.7 ± 2.0	11.0 ± 2.1
90	8.1 ± 3.4	13.1 ± 3.9*	9.1 ± 3.1	10.6 ± 3.4*

*indicates statistical differences vs. intact knee

Shown in Table 14 are the overall *in situ* forces of the intact ACL and the AM and PL bundles as well as the AM and PL grafts for both fixation protocols 45/15 and PL+OTT. In response to the 134 N ATL, the *in situ* force in the intact ACL ranged from 74 ± 23 N at 90˚ to 118 ± 12 N at 30˚. For fixation protocol 45/15 the corresponding value for the combined grafts were 65 ± 21 N to 120 ± 15 N and were not statistically different compared to the intact knee (p>0.05). For fixation protocol PL+OTT, the *in situ* force for the combined ACL grafts were also not statistically different from those of the intact ACL, although a mean difference of 20 N was measured at 90˚ of knee flexion (p>0.05). Further, no statistical differences were found between the two fixation protocols i.e. 45/15 vs. PL+OTT (p >0.05).

Table 14. In situ force (N) of ACL/grafts under 134 N ATL

Angle	ACL In Situ Force (mean ± StDev)		
(degrees)	Intact ACL	45/15	PL+OTT
FE	85 ± 22	75 ± 33	82 ± 28
15	117 ± 14	113 ± 20	111 ± 24
30	118 ± 12	120 ± 15	116 ± 19
45	105 ± 21	106 ± 19	106 ± 23.2
90	74 ± 23	65 ± 21	53 ± 27*

*indicates statistical differences vs. intact ACL

Results for the *in situ* force in the AM and PL bundles and their respective individual grafts were also obtained and compared. For the intact AM bundle, they ranged from 41 ± 23 N at full extension to 91 ± 24 N at 45˚ in response to the 134 N anterior tibial load (Table 15). The corresponding values for the AM graft in each fixation protocol were 35 ± 20 N at full extension to 74 ± 20 N at 45˚ for fixation protocol 45/15, and 44 ± 28 N to 54 ± 18 N for fixation protocol PL+OTT, respectively. Compared to the intact knee, the *in situ* forces for fixation protocol 45/15 were generally a little lower, however no statistical differences were determined. In contrast, the OTT graft carried significantly lower in situ force than the intact AM bundle at all flexion angles, except full extension. When comparing the two fixation protocols with each other, the *in situ* forces in the AM graft for fixation protocol 45/15 were not significantly different than those for the OTT graft at all flexion angles tested.

Table 15. In situ force (N) of AM bundle/grafts under 134 N ATL

Angle	**AM In Situ Force (mean ± StDev)**		
(degrees)	**Intact AM**	**45/15**	**OTT**
FE	41 ± 23	35 ± 20	44 ± 28
15	73 ± 26	59 ± 16	54 ± 30*****
30	91 ± 22	74 ± 20	63 ± 25*****
45	91 ± 24	74 ± 20	69 ± 29*****
90	68 ± 25	54 ± 18	33 ± 23*****

*indicates statistical differences vs. intact AM bundle

The *in situ* forces in the intact PL bundle ranged from 47 ± 2 N at 15˚ to 9 ± 5 N at 90˚ of knee flexion. Those for the PL graft ranged from 54 ± 20 N at 15˚ to 12 ± 10 N at 90˚ of knee flexion for fixation protocol 45/15, and from 58 ± 17 N to 21 ± 12 N for fixation protocol PL+OTT, respectively (Table 16). The in situ force of the PL graft for both fixation protocols were higher in general than the intact PL bundle. The in situ force of the PL graft for fixation protocol PL+OTT was significantly higher than the PL bundle at 30˚, 45˚, and 90˚ of knee flexion, whereas the PL graft for fixation 45/15 was only significantly higher at 45˚ of knee flexion ($p<0.05$).

Table 16. In situ force (N) of PL bundle/grafts under 134 N ATL

Angle	PL In Situ Force (mean ± StDev)		
(degrees)	Intact PL	45/15	PL+OTT
FE	44 ± 18	41 ± 25	40 ± 26
15	47 ± 22	54 ± 19	58 ± 17
30	28 ± 18	46 ± 20	54 ± 18*
45	16 ± 8	32 ± 13*	37 ± 13*
90	9 ± 5	12 ± 10	21 ± 12*

*indicates statistical differences vs. intact PL bundle

Combined Rotatory Loads

Under the combined rotatory loads, the coupled anterior tibial translation of the intact knee was 5.0 ± 3.8 mm at 15˚ and 7.6 ± 4.5 mm at 30˚ of knee flexion while the internal tibial rotation (ITR) was 16.8 ± 3.6˚ and 19.7 ± 3.6˚, respectively (Table 17). After transection of the ACL, the ATT values increased significantly to 9.9 ± 4.3 mm and 11.1 ± 3.9 mm at 15° and 30° respectively ($p<0.05$). Following ACL reconstruction with fixation protocol 45/15, the ATT was 5.9 ± 4.1 mm at 15˚ and 8.3 ± 4.1 mm at 30˚, while the ITR was 16.7 ± 3.5˚, and 20.5 ± 3.6˚, respectively and were not statistically different from that of the intact knee. Results obtained for fixation protocol PL+OTT were 5.1 ± 3.7 mm at 15˚ and 8.3 ± 4.6 mm at 30˚ of knee flexion while the internal tibial rotation (ITR) was 15.8 ± 3.5˚ and 20.2 ± 3.5˚, respectively comparable to the intact knee as there were no significant changes in ATT ($p>0.05$).

Table 17. Anterior tibial translation (mm) under combined rotatory loads

Angle	Coupled ATT (mean ± StDev)			
(degrees)	Intact	ACL(-)	45/15	PL+OTT
15	5.0 ± 3.8	9.9 ± 4.3*	5.9 ± 4.1	5.1 ± 3.7
30	7.6 ± 4.5	11.1 ± 3.9*	8.3 ± 4.1	8.3 ± 4.6

*indicates statistical differences vs. intact knee

Under CRL, the *in situ* force of the intact ACL was 82 ± 17 N at 15˚ and 70 ± 30 N at 30˚ of knee flexion. The corresponding values for fixation protocol 15/15 were 65 ± 24 N and 54 ± 30 N, while for fixation protocol 45/15 the values were 72 ± 19 N and 54 ± 22 N, respectively. As in the case of the applied ATL, no statistically significant differences were found between the *in situ* force of the ACL grafts for both the fixation protocols and the intact ACL.

Results for the *in situ* force in the intact AM and PL bundles and their respective individual grafts were also obtained and compared. The *in situ* force in the intact AM bundle was 48 ± 17 N at 15˚ and 34 ± 18 N at 30˚ of knee flexion. The corresponding values for the AM graft for fixation protocol 45/15, were 31 ± 14 N at 15˚ and 22 ± 18 N at 30˚ of knee flexion, while for fixation protocol PL+OTT they were 37 ± 14 N at 15˚ and 34 ± 17 N at 30˚ of knee flexion (Table 18). No statistical difference was found between the AM graft for fixation protocols 45/15 and PL+OTT and the intact AM bundle at either of the flexion angles tested. The *in situ* forces in the intact PL bundle were 30 ± 14 N at 15˚ and 18 ± 14 N at 30˚ of knee flexion. The *in situ* force in the PL graft were not significantly different from that of the intact PL bundle for both fixation protocols. The corresponding values for the PL graft for fixation protocol 45/15 were 37 ± 16 N at 15˚ and 22 ± 14 N at 30˚ of knee flexion, while for fixation protocol PL+OTT they were 38 ± 14 N and 26 ± 14 N, respectively (Table 18). There was no statistical difference between the two PL grafts and the intact PL bundle as well as in between the grafts of the two fixation protocols for both flexion angles tested, under the combined rotatory loads ($p>0.05$).

Table 18. In Situ force (N) of AM and PL bundles/grafts under combined rotatory loads

Angle	AM In Situ Force (mean ± StDev)			PL In Situ Force (mean ± StDev)		
(degrees)	Intact AM	45/15	PL+OTT	Intact PL	45/15	PL+OTT
15	48 ± 17	31 ± 14	37 ± 14	31 ± 14	37 ± 16	38 ± 14
30	34 ± 18	23 ± 18	34 ± 17	18 ± 14	22 ± 14	26 ± 14

Tables 17 and 18 show that both fixation protocols 45/15 and PL+OTT are capable of restoring rotatory stability similar to that of the intact knee, while Tables 13 and 14 show that the PL+OTT procedure can restore anterior stability up until deep flexion. Therefore in terms of overall in situ force and knee kinematics, the PL+OTT procedure functions comparably to the both the intact knee as well as fixation 45/15. In addition, the force directions were calculated, however, the data was inconclusive, and therefore not used in making conclusions. A larger sample size would be required in order to find any trends.

6.0 DISCUSSION

The results from specific Aim 1 and 2 showed that the knee flexion angle at which each graft is fixed did affect the force distribution of the two grafts in double bundle ACL reconstruction. By fixing the AM graft at 60° of knee flexion in one protocol, and the PL graft at 30° of knee flexion in another protocol, both of those grafts carried significantly higher loads than their intact bundles under an applied 134-N anterior tibial load. In contrast, when the AM graft was fixed at 30° of knee flexion, and the PL graft was fixed at full extension, both of the grafts generally carried lower loads than their respective intact bundles. Therefore, the results showed that the knee flexion angle at which each graft is fixed, affects the outcome of a double bundle ACL reconstruction. This data corroborates what is already known about the importance of the knee flexion angle for graft fixation in a single bundle procedure. Based on the results of Specific Aim 1, it was determined that the PL graft should be fixed at around 15° of knee flexion, while the AM should be fixed at flexion angles less than 60°.

For Specific Aim 2, fixation protocols 15/15 and 45/15 were tested. As per Specific Aim 1, the PL graft was kept constant at 15° of knee flexion, while the AM graft was fixed at either 15° or 45° of knee flexion. Because there are an infinite combination of knee flexion angles to be tested, these two flexion angles were chosen to provide a range of knee flexion angles for graft fixation that would be safe for both grafts. Also, these flexion angles were chosen, due to the ease of application during surgery.

The results of Specific Aim 2 determined that both fixation protocols 15/15 and 45/15 were safe for each of the grafts. Neither the AM nor the PL graft for either fixation protocol carried more load than their respective intact bundle, although the in situ force for the AM graft for fixation protocol 15/15 was generally lower than the intact AM bundle. The anterior tibial translation for fixation 15/15 was also found to be significantly higher than the intact knee under an applied 134-N anterior tibial load, although all of the values were within 2.2 mm of the intact knee kinematics. However, because no significant differences were found for both knee kinematics and in situ force in the grafts, fixation protocol 45/15 was determined to be the most similar to an intact knee. Although it is believed that fixing the AM graft between 15° and 45° degrees of knee flexion, while the PL graft is fixed at 15° of knee will be safe for both of the grafts. Knowledge of an appropriate range is important, in order to produce the best possible outcome.

Specific Aim 3 determined if a double bundle ACL reconstruction procedure with only one femoral tunnel had knee kinematics and in situ force in the grafts similar to that of fixation protocol 45/15 as well as the intact knee. The findings suggested that the overall in situ force and knee kinematics for fixation protocol PL+OTT were similar to both, except at deep flexion. However, since it is understood that the ACL is not as critical at deeper flexion, the PL+OTT procedure could still provide the required knee stability, while also necessitating only a single tibial and femoral tunnel. The in situ force distribution in each graft were significantly different from the intact bundles, since the OTT graft did not carry as much load as the intact AM bundle, and the PL graft carried significantly higher loads than the intact PL bundle. Therefore, in terms of overall performance, the PL+OTT grafts were similar to the intact ACL in maintaining knee stability, although there was a disparity in force distribution.

6.1 FUTURE DIRECTIONS

The Over-the Top procedure has been used previously for single bundle ACL reconstruction procedures, with satisfactory results. Aglietti and co-workers found that the knee stability after a two year follow-up for an OTT procedure was the same as for a single bundle with a single femoral and tibial tunnel [38]. Not only, has this procedure been used for single bundle studies, it is still used to treat young patients today. Since this procedure does not require a femoral tunnel, surgeons can avoid drilling through the open growth plate in young patients. Due to the positive results seen in single bundle procedures, the OTT technique has been studied in a double bundle procedure.

A study was performed by Amis et al., in which a single bundle through the tunnel was compared with a single bundle OTT technique, as well as a double bundle procedure similar to the PL+OTT procedure. The findings of this study were expected, all three procedures restored anterior stability near extension reasonably well, with the OTT and PL+OTT procedures performing better. At deeper flexion, the laxity was the greatest for the OTT graft, while the double bundle technique performed the best.

It is important to note that there were some significant differences between this study and the study performed in Specific Aim 3. One of the major differences is due to the fact that a synthetic graft was used by Amis et al., whereas, the semitendinosus and gracilis tendons were harvested from the specimens tested in Specific Aim 3 [44]. Although, in the past many studies were performed with synthetic grafts, it is generally agreed upon nowadays that a tissue allograft or autograft is a better choice for a replacement graft. The kinematics and force data for Specific

Aim 3 were collected using a robotic/UFS testing system, while the other study used an Instron materials testing machine. Although, many studies have used an Instron, the use of a robotic/UFS testing system allows for the measurement of 6 degree-of-freedom kinematics, and the corresponding force data. Lastly, the method of specimen preparations differed between the two studies. In Specific Aims 1-3, the specimens were kept intact, with no portions being removed, and the fibula fixed in place with a screw.   Due to the numerous differences in the two projects, including graft choice, testing system, and specimen preparation it is believed that the data for Specific Aim 3, is the most accurate.

Despite the imbalanced force distribution, the PL+OTT technique provides positive results in its overall kinematics and in situ force data, as was the case for fixation protocols 30/30 and 60/FE in Specific Aim 1. Therefore further biomechanical testing is recommended, especially under muscle loads. The ACL is most crucial at knee extension, therefore, if the force distribution can be balanced, then the PL+OTT technique still provides anterior and rotatory knee stability similar to the intact knee near extension, while only requiring only one femoral tunnel. In the future, perhaps the drilling of a trough on the lateral femoral condyle could lead to a better fixation of the OTT graft, and allow it to function more similarly to an intact AM bundle. It is recommended that this enhanced procedure be tested, especially under muscle loads in order to determine the performance of the grafts under more in vivo conditions.   As has been done for other ACL reconstruction procedures, all of the variables, including initial graft tension, graft fixation devices, and even knee flexion angle for graft fixation should once again be studied, in order to fully understand the function of each replacement graft in the PL+OTT procedure.

APPENDIX A

RAW DATA – STUDY 1

The knee kinematics and in situ force data collected from the robotic/UFS testing system is shown for each specimen tested in Study 1.

H41014

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACL-IND	ACL-SIM
FE	4.3	10.1	3.4	1.2
15	6.4	15.4	5.8	4.1
30	5.9	15.1	5.5	4.4
60	6.4	11.4	6	5.8
90	4.3	7.3	3.6	3.6

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACL-IND	ACL-SIM
FE	1.7	2.0	0.0	-2.1
15	2.8	1.3	-0.3	0.4
30	-0.3	-2.4	-3.0	-2.6
60	1.6	-1.8	0.4	0.6
90	-2.4	-5.4	-2.1	-2.5

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	5.1	11.4	4	1.6
30	5.7	10.7	5.4	2.9

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	10.0	11.5	8.8	7.1
30	9.8	10.3	9.2	7.5

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	103.6	105.4	124.7	47.4	37.4	22.0	56.4	69.3	104.0
15	126.3	133.1	134.5	67.4	76.5	41.6	59.2	57.3	93.1
30	125.9	120.5	114.1	87.7	96.9	48.0	38.5	24.3	67.2
60	81.4	92.8	88.1	84.5	94.6	70.4	6.2	4.6	18.0
90	65.7	83.5	75.4	74.7	83.1	71.3	10.3	3.2	4.2

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	83.3	84.8	82.1	50.1	43.1	24.7	33.3	42.2	42.2
30	62.8	74.4	89.1	47.3	28.1	34.1	15.6	46.3	46.3

H41012

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	3.5	14.9	4.6	3.2
15	4.8	18.3	5.2	4.9
30	4.6	19.3	4.5	5
60	3.7	12.8	3	4.1
90	2.7	13.3	1.8	2.8

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	-2.2	0.8	-2.5	-2.8
15	-8.6	-3.6	-8.5	-8.9
30	-6.6	-1.6	-7.7	-7.0
60	-1.4	1.3	-3.0	-1.5
90	-2.6	3.1	-4.2	-2.9

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	5.1	11.4	5.8	5.9
30	9.2	15.5	9.9	9.3

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	1.4	12	2.8	5.4
30	2.6	13	4.2	5.4

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	116.9	104.1	128.3	35.0	51.1	32.8	82.9	53.0	95.5
15	117.0	115.3	122.6	59.7	81.8	26.3	57.5	33.5	96.3
30	103.4	111.0	111.0	82.3	102.6	35.4	21.2	8.4	75.6
60	91.8	92.7	87.5	88.2	90.0	51.5	4.6	2.8	36.0
90	84.7	91.8	79.1	83.3	90.3	59.7	2.1	1.5	19.3

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	97.7	93.0	113.7	56.0	52.7	20.7	42.2	40.4	94.1
30	109.9	92.7	108.9	64.4	52.2	39.7	45.9	40.6	70.8

H41021									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	4.4	9.4	1.4	0.6
15	7.9	15.3	2.7	2.8
30	12.8	21.3	5.9	8
60	13.1	18.2	6.1	8.9
90	12.6	17.4	4.9	7.7

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	-0.8	0.0	-1.2	-1.2
15	0.6	1.8	-1.1	-1.1
30	2.2	3.1	0.9	0.5
60	4.1	3.1	0.6	2.5
90	8.2	6.7	4.3	6.7

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	2.5	5.3	-0.9	-2.1
30	8.1	9.7	3.8	2.7

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	15.1	16.4	12.0	11.3
30	20.7	21.4	19.5	18.4

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	63.7	103.3	124.9	28.7	83.3	43.7	37.9	20.3	81.8
15	92.1	128.1	123.3	27.4	112.3	43.6	65.2	15.8	79.7
30	97.1	128.8	123.5	34.9	124.4	54.1	62.7	4.5	70.2
60	66.6	103.0	103.7	55.4	102.5	68.4	13.5	1.1	35.4
90	60.4	91.7	89.0	56.2	92.2	65.4	7.8	1.6	23.7

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	62.3	78.6	77.4	34.5	64.1	26.4	28.6	14.9	52.1
30	26.2	82.8	97.0	24.4	65.0	35.4	3.9	18.1	62.2

H41026									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE				
15	4.1	8.8	6	5.1
30	4.7	14.4	7	5.6
60	5.1	14.4	6.6	6.9
90	5.2	12.7	6.9	7.5

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	1.3	3.7	2.4	1.2
30	1.4	4.0	1.1	-0.5
60	3.4	4.5	2.0	2.2
90	3.1	1.3	2.4	1.8

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	1.8	4.8	3	2.4
30	3.4	7.3	4.5	3.5

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	11.8	14.1	13.3	12.0
30	17.3	20.0	18.3	17.2

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
15	88.4	56.8	71.2	41.2	38.7	24.4	47.3	19.1	47.3
30	125.2	111.4	113.0	70.9	80.2	56.1	54.2	31.2	57.2
60	126.9	101.2	96.3	111.9	94.5	66.8	15.0	6.9	30.3
90	99.4	82.6	84.1	91.3	82.4	64.7	8.2	0.9	19.5

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	73.4	43.3	49.1	34.7	29.9	16.5	40.2	14.3	32.7
30	79.6	54.9	70.6	40.1	14.8	10.9	39.7	40.5	60.8

H41026									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE				
15	4.1	8.8	6	5.1
30	4.7	14.4	7	5.6
60	5.1	14.4	6.6	6.9
90	5.2	12.7	6.9	7.5

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	1.3	3.7	2.4	1.2
30	1.4	4.0	1.1	-0.5
60	3.4	4.5	2.0	2.2
90	3.1	1.3	2.4	1.8

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	1.8	4.8	3	2.4
30	3.4	7.3	4.5	3.5

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	11.8	14.1	13.3	12.0
30	17.3	20.0	18.3	17.2

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
15	88.4	56.8	71.2	41.2	38.7	24.4	47.3	19.1	47.3
30	125.2	111.4	113.0	70.9	80.2	56.1	54.2	31.2	57.2
60	126.9	101.2	96.3	111.9	94.5	66.8	15.0	6.9	30.3
90	99.4	82.6	84.1	91.3	82.4	64.7	8.2	0.9	19.5

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	73.4	43.3	49.1	34.7	29.9	16.5	40.2	14.3	32.7
30	79.6	54.9	70.6	40.1	14.8	10.9	39.7	40.5	60.8

H41028									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	3.1	13.8	3.5	3.9
15	8.5	24.6	9.4	9.4
30	9.3	26.4	10.2	9.8
60	9.9	25	7.3	8.6
90	8.7	18.5	5.4	4.4

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	-0.6	0.6	-1.2	7.4
15	-0.9	-3.4	-1.1	13.7
30	-6.3	-10.1	-7.2	11.0
60	4.9	2.3	3.6	22.6
90	3.2	2.9	3.1	24.3

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	8	14.1	8.3	6.9
30	9.7	13.9	8.9	6.6

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	17.1	19.2	17.7	21.1
30	17.3	18.2	17.2	19.6

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	119.4	100.2	118.0	51.0	51.8	65.1	68.8	61.4	68.7
15	126.3	110.0	109.0	53.2	70.5	43.9	73.2	41.0	96.8
30	127.4	114.8	69.3	76.8	82.1	33.5	50.8	33.4	89.3
60	109.2	101.1	65.4	99.0	99.8	61.6	10.7	2.3	41.3
90	87.0	96.1	70.4	82.3	96.6	61.0	7.2	1.2	9.5

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	101.3	86.8	62.0	45.8	45.5	18.7	55.7	44.9	45.0
30	47.7	74.1	40.2	25.4	38.3	9.7	22.4	43.1	33.0

H41102									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	4.5	6.7	4.5	3
15	9.2	14.7	9	6.4
30	10.9	17.7	10.2	7.2
60	7.3	12	5.8	3.3
90	5.5	8.1	2.8	1.5

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	3.4	4.7	3.2	2.3
15	8.6	8.4	9.0	6.5
30	10.4	9.0	10.3	7.2
60	5.3	5.3	7.6	4.2
90	4.6	4.6	4.6	3.2

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	7.8	11.8	7.8	4.9
30	10.2	14.2	10.2	6.5

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	13.1	15.0	13.5	11.0
30	17.9	19.4	18.5	14.6

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	27.8	46.2	69.7	15.2	39.8	46.6	13.2	6.8	24.0
15	98.7	108.0	126.8	45.1	91.5	69.3	53.9	16.8	58.0
30	105.6	108.1	124.0	57.5	93.3	71.1	48.1	15.1	52.9
60	70.6	96.5	100.7	66.1	92.1	84.9	9.4	4.4	16.2
90	49.9	80.7	90.5	53.3	126.2	84.3	4.0	1.2	6.8

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	66.7	67.6	89.5	39.1	57.1	50.3	27.8	10.9	39.3
30	64.2	66.3	79.3	46.8	52.0	32.9	17.4	14.4	48.4

H41104									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	4.6	8.1	5.9	5.9
15	8.1	14	9	6.5
30	11.1	18.8	11.2	10.4
60	11.3	19.3	10.9	11.1
90	9.5	15.8	8.7	8.8

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	2.1	2.2	2.0	2.0
15	3.5	4.7	4.6	3.1
30	11.4	9.5	9.7	9.9
60	14.5	13.4	13.7	15.2
90	10.5	8.2	11.1	11.1

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	6.1	11.6	6.4	4.2
30	9.7	15.1	9.7	7.7

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	14.1	15.6	13.8	11.6
30	22.8	23.0	22.5	21.8

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	86.9	94.9	98.3	58.6	69.8	69.8	28.5	26.0	29.0
15	108.2	115.7	128.4	71.0	88.6	50.3	37.4	27.3	78.7
30	109.6	118.6	124.1	78.2	102.6	76.8	31.5	16.2	49.6
60	97.5	111.1	110.4	87.0	106.7	100.6	11.4	4.6	10.1
90	82.0	91.6	90.9	74.2	91.7	90.1	8.9	0.3	1.5

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	81.2	73.0	93.5	61.4	56.0	46.2	20.5	18.2	48.6
30	69.9	80.8	85.4	59.9	63.4	48.6	10.3	17.7	37.6

H41119									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	9.5	16.8	14.5	12.8
15	10.6	20.1	16.8	15.4
30	11.8	19.8	16.7	16.3
60	9.2	12.3	11.3	12
90	8.1	9.8	8.9	9.8

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	6.6	9.5	8.9	8.3
15	6.9	10.1	9.7	9.2
30	7.9	9.6	9.6	9.5
60	5.9	5.7	6.4	6.8
90	6.6	5.1	5.8	6.5

Com Rot - ATT

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	7.6	18.4	16.8	15.9
30	10.1	18.3	16.8	16

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	6.1	10.4	9.5	9.3
30	7.7	10.9	10.9	9.4

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	124.2	38.0	72.2	78.2	22.0	15.9	49.8	18.1	59.6
15	168.2	84.2	112.7	74.9	53.2	24.7	93.9	31.2	89.6
30	145.6	52.6	84.4	81.3	44.5	20.5	66.2	8.2	65.1
60	76.7	42.3	17.9	64.3	41.0	10.5	14.7	4.5	7.8
90	53.6	25.2	15.4	41.2	33.2	13.6	12.5	8.2	2.2

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	96.0	46.9	102.1	16.1	32.4	8.9	82.5	15.9	95.7
30	94.4	29.4	79.0	38.8	26.7	19.6	57.0	5.2	59.7

H41222

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	4.3	6.5	5.8	4.8
15	9.2	12.4	9.7	9.9
30	10.2	14.7	9.9	11.3
60	9.4	16	7.4	9.6
90	7.6	14.6	4.3	7.2

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	-1.4	-2.1	-3.3	-3.1
15	1.0	1.0	0.0	-0.4
30	-0.9	0.6	-0.9	-1.0
60	4.0	0.4	1.8	4.3
90	-3.4	-4.8	-6.3	-2.2

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	5.1	6.8	4.9	4.6
30	6.8	9.3	6.2	5.3

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	26.2	23.1	25.6	28.5
30	29.0	29.0	28.5	27.0

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL - Sim
FE	65.5	69.8	98.6	40.4	48.7	49.0	25.3	21.3	49.9
15	85.4	114.2	107.8	53.5	81.7	42.8	32.3	32.7	65.1
30	96.4	107.9	112.2	65.5	93.8	47.2	31.8	14.1	65.3
60	91.0	94.1	88.3	85.7	92.7	64.8	10.0	1.4	24.7
90	83.6	79.5	80.0	84.0	80.1	68.3	7.4	1.4	11.8

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	60.3	69.5	69.3	42.6	40.0	18.1	18.0	29.7	53.3
30	32.3	50.0	69.9	18.5	23.5	15.3	14.4	27.8	56.7

H50107									

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	2.7	5.2	5.3	2.7
15	5.7	10.1	8.4	5.5
30	6.9	12.8	9	7
60	6.5	14.1	7.3	6.9
90	7.1	15.1	7.5	7.8

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL-def	ACLR-IND	ACLR-SIM
FE	-0.3	1.1	-0.4	-2.9
15	-2.5	0.2	-1.7	-4.2
30	-2.9	0.9	-2.5	-3.3
60	0.4	6.3	0.8	0.8
90	5.6	11.4	5.7	6.7

Com Rot - ATT

	Intact	ACL (-)	ACLR-IND	ACLR-SIM
15	1.6	5.2	4.5	1.6
30	3.4	7.5	5.7	3

Com Rot - ITR

	Intact	ACL-def	ACLR-IND	ACLR-SIM
15	12.9	17.3	16.2	12.8
30	17.7	21.9	20.8	17.4

AP 134 - In Situ Force

	ACL	ACL - Ind	ACL - Sim	AM	AM - Ind	AM - Sim	PL	PL -Ind	PL -Sim
FE	86.7	67.4	100.6	34.1	27.9	39.0	53.8	39.9	62.1
15	92.0	89.6	101.3	41.4	65.5	38.9	50.6	24.2	62.9
30	91.6	84.8	97.1	69.4	78.8	59.6	22.3	6.2	37.6
60	87.0	73.8	75.8	79.4	74.0	67.7	7.7	0.5	8.6
90	75.0	63.6	63.3	75.9	63.4	60.8	1.3	0.7	3.2

Com Rot - In Situ Force

	ACL	ACL-IND	ACL-SIM	AM	AM-IND	AM-SIM	PL	PL-IND	PL-SIM
15	75.8	61.3	79.3	39.4	40.5	33.2	36.6	20.8	47.2
30	87.4	60.2	80.5	51.9	42.0	52.0	35.7	18.4	29.1

APPENDIX B

RAW DATA – STUDY 2

The knee kinematics and in situ force data collected from the robotic/UFS testing system is shown for each specimen tested in Study 2.

H50909

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	3.9	6.4	3.9	3.3
15	6.1	15.4	6.8	7.3
30	9.7	21	10	11.2
45	9.4	21.6	9.3	11.3
90	7.4	15.3	6.3	8.4

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	1.7	3.5	2.0	1.7
15	-2.2	1.1	-1.3	-1.3
30	0.2	2.5	0.0	0.0
45	-1.1	-0.2	-1.7	-0.6
90	0.0	-3.0	-0.3	0.2

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	5.1	11.4	5.8	5.9
30	9.2	15.5	9.9	9.3

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	13.7	16.7	13.9	14.6
30	20.2	21.1	19.8	19.3

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	67.8	89.1	70.4	16.9	52.2	34.8	58.9	39.1	36.0
15	112.3	111.1	109.0	21.9	71.0	68.0	90.7	41.3	41.2
30	128.2	122.4	112.8	57.9	95.3	79.0	70.7	27.3	34.1
45	116.6	108.0	107.4	70.2	96.3	85.0	46.4	11.9	22.5
90	103.2	97.4	90.2	84.7	96.6	86.5	18.7	1.9	4.3

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	95.3	90.8	94.8	21.0	52.7	42.3	74.5	39.4	53.4
30	101.8	90.8	92.0	53.3	58.4	46.0	48.5	33.8	47.9

H50926

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	3.4	10	2	3.9
15	7.9	19.1	6.2	8.8
30	8.4	19.9	6.6	9.5
45	8.7	18.8	6.9	9.6
90	7.3	12.3	5.2	7.4
120	8.6	14	6.5	9

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	2.7	3.4	0.0	1.2
15	5.5	4.4	1.1	1.8
30	2.1	0.1	-1.6	-0.4
45	5.6	2.3	1.9	3.8
90	4.7	3.1	1.4	2.2
120	6.9	4.4	0.0	2.5

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	7.7	15.6	5.8	8.7
30	9.2	16	7	10.3

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	22.0	23.8	18.9	21.7
30	23.8	22.5	20.7	23.4

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	82.7	95.9	71.3	61.9	75.0	65.1	21.7	21.6	54.1
15	123.4	117.7	109.6	99.3	74.8	84.7	25.1	43.3	25.9
30	120.4	123.1	115.9	108.6	95.4	73.2	13.8	27.8	43.1
45	104.2	100.4	93.9	98.1	83.8	69.9	15.0	18.8	24.9
90	79.7	75.6	67.7	78.8	64.5	51.5	4.1	13.1	16.6
120	86.1	73.1	66.6	80.8	54.6	41.9	8.8	21.3	26.7

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	85.8	70.9	57.1	54.0	50.7	26.1	31.9	39.4	31.3
30	61.3	71.0	83.5	38.1	39.3	16.6	26.1	33.8	34.5

H50930

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	2.9	7.3	2.7	2.7
15	3.8	13.9	4.5	4.2
30	4.3	15.6	5.6	5.6
45	4.7	15.6	6.4	6.3
90	3.3	6.6	4.7	4.4
120	3.5	7.9	5	4.8

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	-0.9	0.5	-1.0	-0.9
15	-2.1	-0.3	-2.0	-2.9
30	-7.7	-6.1	-8.1	-7.5
45	-5.2	-4.2	-4.4	-4.9
90	-0.8	-3.4	-1.6	-1.4
120	-0.6	-3.1	-0.9	-0.7

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	1	7.5	2.8	1.9
30	2.6	9	4	3.6

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	15.4	18.3	17.6	17.3
30	14.5	16.6	15.8	15.2

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	95.0	73.4	62.9	28.8	44.0	32.1	68.8	29.5	38.5
15	135.5	114.6	118.2	21.9	80.6	63.4	113.7	36.2	55.6
30	127.0	114.8	119.7	42.6	91.7	74.7	84.6	23.6	45.5
45	112.4	101.9	100.6	52.8	87.0	73.9	59.7	15.5	27.4
90	75.8	42.2	43.6	61.9	39.2	34.1	14.1	3.2	9.9
120	93.5	61.2	70.2	68.3	45.1	41.2	25.3	17.0	30.0

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	75.4	72.5	75.0	15.8	49.2	41.4	60.7	23.4	33.7
30	84.9	59.7	62.1	27.5	34.5	31.9	57.5	25.2	30.8

H51003

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	4.6	10.3	6.0	6.6
15	5.2	14.7	7.7	8.6
30	5.6	14.8	8.7	9.4
45	5.0	12.2	8.4	8.9
90	3.9	9.6	7.4	7.9
120	4.9	10.8	8.1	9.0

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	-2.2	-0.5	-1.9	-1.9
15	-2.1	1.2	-0.4	-0.8
30	-2.1	-0.8	-1.5	-1.8
45	-2.6	-1.7	-1.5	-1.6
90	-1.6	0.6	0.1	0.2
120	1.0	4.7	2.2	7.6

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	1.7	6.0	3.7	3.9
30	2.2	5.0	3.1	3.5

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	17.2	20.4	20.0	20.0
30	17.7	20.5	19.7	19.4

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	94.9	61.0	48.4	84.5	33.3	22.4	11.1	27.8	27.3
15	124.3	99.7	96.5	118.0	54.8	61.4	6.6	45.1	35.1
30	124.1	91.3	93.4	118.9	62.1	60.3	8.8	29.2	33.2
45	114.1	83.2	64.1	107.0	63.7	40.7	9.2	19.7	23.5
90	78.3	39.2	34.7	67.5	36.5	20.8	14.0	2.9	14.1
120	61.7	27.8	24.4	54.1	26.0	17.8	9.4	1.8	14.0

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	72.4	32.8	23.4	58.5	12.0	11.5	15.0	21.0	13.3
30	47.3	28.8	22.6	36.5	16.4	4.1	17.0	14.0	18.4

H51213R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	4.3	7.9	4.8	6.1
15	6.2	11.2	7.6	9.3
30	9.3	14.1	10.7	12
45	10.1	15	11.3	12.4
90	9.6	13.7	9.7	10.8
120	8.1	13.4	8.6	9.3

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	3.7	6.6	3.8	6.1
15	3.7	6.1	3.7	5.6
30	7.8	7.7	8.1	9.5
45	9.2	7.9	9.7	10.4
90	11.7	9.6	11.8	12.5
120	8.4	8.7	10.3	10.6

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	7.7	11.7	9.4	10.1
30	11	13.1	11.6	12.3

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	11.9	13.3	13.0	13.2
30	16.6	17.1	17.4	17.4

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	94.0	90.2	73.9	58.5	53.1	40.8	35.9	37.2	33.4
15	115.5	105.1	88.7	76.7	55.8	47.3	38.8	49.5	41.5
30	102.8	97.1	62.2	70.5	68.5	36.5	32.5	29.1	26.3
45	85.3	74.1	57.3	54.1	64.0	49.2	31.9	10.4	8.2
90	83.1	89.8	63.2	53.0	88.3	60.0	30.6	2.7	3.2
120	84.3	76.4	66.1	26.2	57.2	50.7	61.5	20.0	16.0

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	71.5	84.6	39.7	40.3	65.3	15.3	31.3	21.2	24.5
30	32.1	32.9	17.7	18.2	30.8	11.0	14.1	3.8	7.1

H60110

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	3.3	7.6	5.3	5.8
15	6	14	9.9	10
30	6	13.5	10.1	10.3
45	6.9	12.1	10.8	11
90	3.6	6.3	5.8	5.8
120	7.1	10.1	8.3	8.4

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	1.04	2.9	2.6	-0.2
15	4.33	5.1	7.1	7.7
30	5.7	5.3	8.2	8.6
45	9.38	8.7	11.7	12.3
90	3.78	2.7	5.8	6.0
120	11.52	10.6	12.6	13.1

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	5.5	14	9.8	9.4
30	6.8	13.6	10.6	11

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	12.3	16.8	15.9	15.4
30	15.69	18.4	18.6	18.8

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	87.0	59.5	59.1	25.5	19.3	15.0	61.7	41.0	45.6
15	114.4	91.0	94.5	42.9	22.7	24.5	71.8	68.9	70.1
30	99.9	87.9	83.0	58.4	36.4	34.5	41.6	51.7	49.4
45	82.5	69.8	58.7	64.0	45.3	32.6	12.7	25.3	26.9
90	61.0	38.8	44.5	61.1	23.4	33.6	3.4	15.4	11.6
120	72.3	75.6	63.0	56.1	50.1	38.9	17.1	28.0	24.7

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	102.8	79.0	68.9	41.6	36.2	24.3	62.2	46.0	45.0
30	90.4	54.2	57.7	40.5	23.6	28.2	50.2	31.3	29.5

H60203L

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	3.2	6.9	4.1	3.9
15	9.5	18.5	11.6	11.2
30	8.9	18.6	12.3	11.6
45	6.7	14.8	9.2	8.8
90	6	14.2	8	7.5
120	5.5	14	6	5.3

AP 134 - Interior Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	0.5	2.5	0.9	1.1
15	8.2	9.3	9.0	8.2
30	4.2	5.4	6.7	5.8
45	-1.0	-1.1	0.1	0.0
90	-0.2	2.3	1.6	1.5
120	-3.6	0.4	-3.3	-3.4

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	9.7	15.9	12.2	11.4
30	11.8	16.2	14.5	13.6

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	18.8	22.8	20.6	20.2
30	21.1	24.0	23.7	23.5

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	75.0	70.3	68.7	38.1	27.1	18.8	44.9	47.7	50.4
15	127.9	118.1	114.7	38.0	45.5	40.7	90.7	73.7	75.0
30	119.4	112.5	113.5	64.0	59.8	60.4	55.8	53.9	54.8
45	113.8	93.5	102.1	76.4	68.9	75.1	38.9	25.3	27.4
90	83.9	86.7	86.2	60.1	57.2	56.3	24.1	30.9	30.6
120	83.4	71.6	84.1	46.7	13.8	29.3	37.6	58.6	56.8

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	101.7	68.0	82.5	45.8	13.7	29.4	56.8	54.7	54.4
30	80.5	57.3	56.0	51.9	24.1	20.5	29.0	36.2	36.2

H60210R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	4.9	12.9	4.9	5.5
15	6.4	16.2	6.5	7.1
30	6.2	15.7	6.6	7.6
45	7	14.5	7.5	8.8
90	4.8	8.2	4.7	5.8
120	4.8	8.2	3.9	5.3

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	-0.1	-0.5	0.6	-0.8
15	-1.9	-3.6	-1.4	-3.0
30	-4.7	-4.9	-2.9	-4.8
45	2.6	1.9	2.7	1.7
90	2.2	2.1	2.0	2.5
120	1.4	3.1	1.5	1.5

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	4.6	8.6	4.5	5.9
30	4.9	6.7	5.3	5.9

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	11.1	12.1	12.2	12.4
30	11.7	11.8	13.0	12.6

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	133.9	146.4	134.1	76.2	91.5	37.1	58.3	55.0	97.5
15	145.7	143.4	140.3	103.1	103.1	63.7	42.7	41.0	76.6
30	127.7	135.0	134.2	103.9	106.5	80.4	23.8	28.9	53.8
45	112.8	124.5	106.4	105.7	89.5	76.0	7.3	35.7	30.4
90	86.0	91.1	63.4	87.8	65.7	60.4	2.2	25.5	3.8
120	72.8	87.7	74.5	74.6	54.8	66.4	2.1	33.0	9.8

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	50.5	57.7	50.7	34.1	34.9	12.2	16.6	23.3	39.4
30	23.8	26.3	11.5	21.5	19.9	11.9	3.8	7.1	10.8

H60217R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	15/15
0	5.5	7.7	6.1	5.4
15	7	14.7	8.3	8
30	10	21.3	11.6	11.3
45	11.2	22.3	12.7	11.9
90	7.2	13.9	8.5	8
120	8	14.7	7.9	7.7

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	15/15
0	-5.1	-3.4	-3.9	-3.4
15	-9.8	-3.3	-8.5	-8.7
30	-18.2	-11.2	-17.7	-17.3
45	-24.2	-14.7	-21.8	-22.1
90	-21.0	-14.4	-19.7	-19.0
120	-23.7	-16.1	-24.1	-23.2

Com Rot - ATT

	Intact	ACL (-)	45/15	15/15
15	-2.7	0.3	-2.4	-2.5
30	-0.8	2.9	0.4	-0.1

Com Rot - ITR

	Intact	ACL (-)	45/15	15/15
15	13.1	18.6	16.9	16.4
30	13.9	16.9	16.8	16.8

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
0	50.7	53.6	64.8	26.2	9.7	12.4	24.7	46.8	52.5
15	74.2	98.1	91.8	43.0	28.2	19.3	31.3	71.6	72.9
30	89.6	92.0	94.8	69.4	45.5	40.3	20.3	46.6	54.7
45	84.3	81.8	86.2	77.9	55.3	61.1	7.2	27.2	25.5
90	56.4	66.2	62.7	57.8	56.0	51.1	1.9	11.1	12.8
120	50.4	53.7	56.6	51.2	38.6	29.3	1.8	16.5	27.4

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL 15/15	AM	AM 45/15	AM 15/15	PL	PL 45/15	PL 15/15
15	84.8	93.7	91.3	56.0	32.0	26.7	29.1	62.3	67.4
30	103.2	67.1	81.1	78.5	16.4	30.9	24.8	50.7	50.5

APPENDIX C

RAW DATA – STUDY 3

The knee kinematics and in situ force data collected from the robotic/UFS testing system is shown for each specimen tested in Study 3.

H60915L

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	3.1	6	1.1	1.5
15	8	15.2	4.7	5.9
30	10.8	17.5	7.3	9.4
45	11.2	14.5	9.2	11.6
90	7.7	8.4	7.4	10.4

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	1.3	2.4	-1.0	-0.5
15	10.0	8.8	6.6	8.0
30	6.8	6.3	5.1	7.9
45	6.5	6.2	6.5	10.8
90	5.0	4.2	5.9	9.6

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	7.1	11.3	4.3	5.6
30	9.7	11.6	6.3	10

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	18.2	19.7	15.8	17.1
30	17.9	18.8	15.9	19.7

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	84.0	103.2	100.2	55.8	40.1	41.0	28.3	64.6	59.9
15	128.4	134.6	124.0	110.0	75.0	69.6	18.5	59.9	54.5
30	117.0	129.5	123.0	112.2	95.8	84.6	4.9	33.9	38.5
45	73.5	88.4	113.2	76.4	64.0	86.5	3.1	24.5	26.9
90	23.7	37.7	60.7	28.6	37.5	51.3	5.3	0.9	9.4

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	81.9	91.2	79.2	68.5	48.6	43.1	13.5	43.1	36.3
30	17.9	49.1	83.4	19.1	15.5	48.7	1.6	35.0	35.5

H60920L

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	2.8	2.8	4.4	4.3
15	5	12.7	7.8	7.6
30	5.6	14.3	8.2	7.9
45	4.9	12.1	7.5	8.1
90	2.4	6.4	4.5	5.7

AP 134 - Interior Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	0.1	0.1	-0.2	-0.1
15	1.1	2.3	2.0	0.7
30	4.1	5.6	7.4	6.0
45	4.7	4.7	6.7	5.5
90	0.2	0.7	2.3	1.1

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	2	8.7	5.8	5.4
30	3.6	9.9	8.5	7.7

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	12.7	17.2	17.2	16.7
30	23.1	25.8	28.1	26.5

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	65.8	27.5	39.2	28.8	15.4	29.7	42.8	12.4	20.0
15	118.4	84.3	92.5	46.6	63.9	52.7	72.4	20.5	40.0
30	114.2	97.3	95.4	72.1	84.9	70.9	42.5	12.6	24.8
45	100.4	86.1	78.7	82.4	79.6	49.8	19.3	6.7	29.4
90	80.9	53.8	20.4	81.0	54.4	4.5	8.4	2.0	17.6

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	92.0	63.0	66.5	38.8	46.9	35.7	53.3	16.6	31.3
30	106.9	59.1	72.4	58.8	51.9	33.2	48.4	7.2	39.6

H60922L

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	2.8	6.3	3.4	3.2
15	6.1	17.6	6.9	6.8
30	9.6	23.5	10.3	10.6
45	10	24.9	11.4	13.1
90	7.4	14.1	8.9	12.3

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	0.5	1.3	0.4	-0.7
15	7.6	3.5	3.8	0.2
30	10.3	3.5	3.6	-0.9
45	12.5	5.0	3.2	0.1
90	10.7	7.0	7.7	5.9

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	0.1	4.5	1.4	1.3
30	4.1	7.8	5	5.4

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	26.2	22.9	18.7	14.4
30	29.3	26.7	29.7	28.0

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	76.9	56.6	71.4	27.3	23.5	49.8	52.2	34.3	21.8
15	128.1	132.5	136.8	97.2	53.8	72.7	30.9	79.7	64.8
30	139.4	135.2	136.0	123.6	59.7	61.2	18.2	76.5	74.8
45	136.8	130.0	140.9	135.4	92.7	96.3	13.8	37.5	44.7
90	93.9	89.4	67.8	104.0	70.4	47.8	12.2	20.0	20.8

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	66.4	72.8	75.9	33.7	33.9	39.9	35.5	40.2	36.0
30	25.8	36.8	58.1	17.0	19.2	42.5	18.6	17.6	16.3

H61003R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
0	5	7.2	5.7	5.3
15	10	13.2	9.7	11
30	11.4	16.5	12.2	13.3
45	12.9	19.2	14.4	14.9
90	12.3	17.2	14.6	17.3

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
0	-2.4	-0.8	-2.6	-3.3
15	-10.8	-6.6	-10.8	-11.5
30	-12.0	-7.8	-10.6	-12.4
45	-9.2	-4.7	-7.4	-9.7
90	-8.2	-5.5	-5.2	-5.3

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	3.5	6.9	4.7	3.5
30	5.7	8.2	6.5	5.7

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	14.2	15.9	15.3	15.0
30	16.4	16.9	16.9	16.6

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
0	86.2	73.8	85.4	37.0	16.8	31.4	50.4	59.6	55.1
15	106.1	115.6	76.4	66.1	62.9	10.4	39.9	53.1	67.6
30	121.8	117.5	112.2	87.8	61.7	35.8	34.4	56.1	76.8
45	115.6	112.8	105.6	95.7	66.6	55.5	20.3	46.6	50.2
90	89.7	53.8	17.8	84.2	50.2	2.9	6.2	3.8	15.2

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	98.7	74.5	94.6	60.9	23.1	48.9	38.1	52.7	46.7
30	48.8	25.3	57.5	30.3	7.8	43.3	18.7	19.5	14.4

H61101L

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	4.1	2.1	4.4	3.9
15	13.3	10.1	14.8	13.0
30	10.8	7.6	12.6	10.1
45	10.1	6.8	11.2	8.5
90	11.8	11.9	13.7	10.8

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	8.9	15.9	10.3	9.3
30	11.1	15.1	12	11.1

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	19.3	22.2	20.5	19.4
30	19.3	20.7	20.1	19.1

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	4.5	12.1	4.9	4.6
15	9.3	19.6	10	9.3
30	10.8	21	11.1	10.4
45	10.7	16.7	11.2	11
90	10.2	12.9	10.8	11.8

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	123.1	122.0	112.2	74.0	56.6	70.0	49.2	65.7	42.8
15	126.2	125.5	119.3	87.9	63.1	61.2	38.6	63.1	58.5
30	113.8	126.3	110.2	96.1	55.5	48.8	18.1	71.1	61.4
45	79.2	91.5	70.8	64.7	51.2	38.9	17.7	40.7	32.3
90	57.3	48.7	12.6	45.9	43.7	8.1	11.7	8.8	5.1

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	92.5	93.0	86.8	71.6	48.9	55.3	22.4	44.0	31.9
30	64.4	51.6	50.6	45.4	27.2	37.7	22.0	24.4	13.2

H61121R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	2.6	6.5	3.4	3.2
15	4	12.5	4.5	4.9
30	6.1	18	6.3	7.2
45	7.7	19.4	8.3	9.2
90	5.7	13.1	6.4	8.9

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	-1.5	-1.2	-2.4	-2.3
15	-5.2	-2.9	-3.4	-4.6
30	-11.0	-7.3	-10.4	-10.9
45	-7.6	-3.7	-6.0	-5.3
90	-2.9	-1.2	-1.3	-1.0

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	0.7	7	1.4	1.2
30	3.3	8	4.1	4.4

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	7.8	11.3	8.7	8.3
30	9.7	11.6	10.7	10.4

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	92.9	76.2	80.3	61.9	44.3	48.2	31.6	32.4	33.0
15	134.3	131.4	133.4	79.0	70.5	83.5	55.4	61.3	50.3
30	138.0	144.9	145.0	104.0	111.9	114.3	34.2	33.8	31.0
45	128.6	142.6	136.5	113.0	121.4	120.8	15.8	21.2	15.7
90	92.6	99.9	87.1	92.7	93.5	73.6	3.5	8.0	13.6

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	85.3	81.6	78.1	47.7	39.7	49.7	38.0	42.6	28.4
30	71.7	78.2	67.7	53.0	55.4	49.7	18.9	22.8	18.1

H61129R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	4.5	14.3	7.1	6.5
15	5.5	19.9	8.5	7.7
30	5.8	21.2	8	7.3
45	8.5	23.5	11.5	12.3
90	6	15.6	8.6	10.5

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	-3.6	0.0	-4.7	-3.9
15	-8.9	-3.2	-9.3	-8.7
30	-14.1	-9.0	-14.3	-13.3
45	-6.5	-3.3	-6.5	-6.9
90	-7.4	-4.7	-6.0	-5.9

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	3.9	11.5	7.3	5.7
30	4.1	10.5	6.8	5.2

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	14.0	17.3	16.8	15.8
30	13.8	16.0	15.6	15.0

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	116.1	104.1	115.2	72.1	78.3	107.8	44.3	26.0	7.8
15	124.6	123.7	139.7	94.9	78.5	104.6	29.7	45.4	35.3
30	112.7	119.6	133.3	101.3	57.9	76.3	11.5	62.2	58.1
45	120.7	116.7	120.9	104.5	65.3	92.5	17.6	51.7	29.0
90	85.3	79.9	70.7	66.8	61.8	28.8	19.4	21.5	42.9

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	99.2	49.6	63.7	62.0	24.6	39.0	37.7	25.4	26.4
30	82.3	52.3	71.5	55.2	23.0	52.2	27.7	30.7	19.3

H70424L

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	4.8	11.9	0.7	-0.6
15	9.3	19.1	5.3	3.6
30	12.2	20.8	8.1	6.6
45	12.8	19.5	10.5	9.2
90	12.1	14.6	11.1	11.7

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	5.1	4.4	4.3	2.2
15	9.3	6.5	8.0	6.1
30	11.1	6.4	7.7	6.0
45	8.1	5.5	6.6	4.8
90	9.9	8.1	8.8	9.5

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	8.5	11.7	5	3
30	11.6	13.4	8.9	7.4

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	23.4	25.3	20.9	19.9
30	26.3	27.3	24.9	24.8

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
FE	84.2	102.3	105.7	11.4	20.1	15.1	85.4	84.3	97.0
15	113.7	105.1	110.1	27.9	23.7	21.0	91.8	83.1	96.6
30	108.8	106.9	117.2	42.7	61.1	56.0	67.2	47.1	64.1
45	90.3	94.0	100.0	57.4	65.5	57.6	33.1	29.0	45.0
90	47.5	39.1	57.1	43.2	31.6	28.7	4.4	7.7	34.3

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	62.9	78.2	85.3	37.4	15.8	24.9	26.1	62.8	60.7
30	30.9	56.4	68.6	25.9	10.8	11.4	5.1	47.8	58.1

H60217R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	2.9	5.3	3.9	3.4
15	5.9	10.9	7.7	6.5
30	8.6	15.5	9.5	9.4
45	9	15.6	10.6	9.4
90	5.2	10.1	6.3	5.4

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	2.9	5.3	3.9	3.4
15	5.9	10.9	7.7	6.5
30	8.6	15.5	9.5	9.4
45	9	15.6	10.6	9.4
90	5.2	10.1	6.3	5.4

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	-2.7	0.3	-2.4	-2.5
30	-0.8	2.9	0.4	-0.1

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	13.1	18.6	16.9	16.4
30	13.9	16.9	16.8	16.8

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
0	53.4	31.5	38.2	34.5	23.8	18.7	19.5	11.4	21.1
15	93.6	89.5	89.0	55.7	48.3	35.3	38.0	42.0	53.7
30	102.1	117.2	99.1	80.6	92.6	41.5	21.5	24.6	57.8
45	105.1	96.3	104.6	100.1	69.1	62.2	5.1	27.3	42.8
90	89.2	73.7	77.7	91.3	55.7	45.4	2.8	18.2	32.9

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	84.8	93.7	91.3	56.0	32.0	26.7	29.1	62.3	67.4
30	103.2	67.1	81.1	78.5	16.4	30.9	24.8	50.7	50.5

H60217R

AP 134 - Anterior Tibial Translation (ATT)

	Intact	ACL (-)	45/15	OTT
FE	3.9	7.5	3.5	1.6
15	10.5	19.4	10.2	7.6
30	12.8	23.3	12.7	11
45	12.9	23.6	12.4	11.1
90	12.1	19	12.6	11.9

AP 134 - Internal Tibial Rotation (ITR)

	Intact	ACL (-)	45/15	OTT
FE	4.1	2.1	4.4	3.9
15	13.3	10.1	14.8	13.0
30	10.8	7.6	12.6	10.1
45	10.1	6.8	11.2	8.5
90	11.8	11.9	13.7	10.8

Com Rot - ATT

	Intact	ACL (-)	45/15	OTT
15	7.7	15.9	9.7	8.9
30	10	15.1	11.8	11.1

Com Rot - ITR

	Intact	ACL (-)	45/15	OTT
15	15.7	20.6	17.9	16.4
30	16.5	21.2	21.0	19.7

AP 134 - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
0	62.4	54.2	68.5	24.1	31.7	29.4	39.1	22.7	39.3
15	94.6	89.8	83.2	44.0	53.7	30.8	50.8	36.2	53.4
30	108.0	101.9	88.3	76.5	61.0	36.9	31.6	41.6	54.2
45	99.1	98.2	85.9	81.4	66.6	32.0	17.9	35.1	56.8
90	75.3	70.1	60.0	64.7	41.0	41.6	11.0	29.6	20.4

Com Rot - In Situ Force

	ACL	ACL 45/15	ACL OTT	AM	AM 45/15	AM OTT	PL	PL 45/15	PL OTT
15	77.1	46.3	74.3	38.8	15.8	13.5	38.8	30.9	61.2
30	32.5	10.8	34.9	24.8	5.6	11.4	14.0	8.1	23.8

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