A Biomechanical Analysis of Different Anterior Cruciate Ligament Surgical Techniques

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B.S.E. Biomedical Engineering, University of Connecticut, Storrs, 2014

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science At the University of Connecticut, Storrs

May 2016
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University of Connecticut
2016
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Abstract

Anterior cruciate ligament (ACL) tears are one the most prevalent activity-related injuries among young athletes in the United States. It generally takes up to nine months for any athlete or non-athlete to fully recover. ACL reconstructive surgeries are typically done using a patellar tendon graft or hamstring tendon graft. Right now, there is some debate as to which type of graft surgery is best, as surgeon preferences between the two differ. Thus, the primary aim of this pilot study was to compare the aforementioned ACL surgical techniques. In addition, a secondary aim was to provide physical therapists and patients with real-time feedback about the progress of the recovery over time when performing a common physical therapy exercise regimen.

A total of 23 participants were enrolled in the study: 15 in the control group, and 8 in the ACL group (4 with patellar tendon graft, 3 with hamstring tendon graft, and 1 with quadriceps tendon graft). Each subject visited the lab six times in twelve weeks, and was asked to complete chair squats, sit-to-stand exercises, and a walk on a treadmill each time. The results of this pilot study demonstrate that the surgical techniques can be evaluated using a dynamic multi-system approach. Between the systems there are a total of twenty-one variables: nine from the motion capture system, six from the electromyography (EMG) sensors, and six from the force platform. The significant parameters included knee flexion, maximum muscle activity from the muscles around the knee, and forces and moments of the body overall.

The study compares subjects within the control group as well as the subjects in the ACL-Reconstruction (ACL-R) group. Within the control group, the subjects are compared between males and females. In the ACL-R group, the subjects were compared between males and females and the type of surgery. When considering the knee flexion data the hamstring graft is more beneficial than the patellar tendon graft in terms of showing progress over the course of the study.
With regards to EMG and force platform results, the data proved either inconclusive or favoring the patellar tendon graft technique during the chair squat and sit to stand activities.

ACL injuries have become a commonplace in sports thus making it imperative to develop effective physical therapy techniques that enable athletes to regain the strength necessary to compete. With this research, we can conclude that real-time feedback may be a useful approach for ACL rehabilitation, and in determining which surgical approach may be most ideal for recovering patients.
1.0 Introduction

Anterior cruciate ligament (ACL) injuries are one of the most prevalent in the United States and around the world. Just in the United States alone, there are a staggering 100,000-200,000 injuries each year (WebMD). Currently, it takes up to nine months for an athlete or non-athlete to fully recover from this type of injury. For some, this may be too long, especially those whose livelihood depends on his or her ability to participate in sports. This type of injury is common in both young adults and individuals over the age of forty (N.A. Mall, P.N. Chalmers). Given these facts, it is important to study the current physical therapy approach and patient outcomes. The current gold standard of rehabilitation from ACL injuries is based on mainly visual cues and suggestions from the physical therapists which has some disadvantages. It is important to improve on these processes with the more advanced technology that is available in the world today. Also, it is vital to analyze and compare the different ACL surgical techniques and identify patient outcomes. With this new technique for rehabilitation, the hope is that it could help both the physical therapists and the patients in the future by providing real-time feedback about progress over time.

People with an ACL injury spend a lot of time, money, and effort on the therapy process both with and without a physical therapist present. The overarching goal of the study is to compare the recovery timelines of the different surgical techniques. A secondary goal is to provide physical therapists and patients with real-time feedback about the progress of the recovery over time when performing a common physical therapy exercise regimen. A third goal is to evaluate the time it takes someone to do the given activity thus possibly analyzing the early warning signs of osteoarthritis. The data collection will be done using three different systems: an Optitrack Motion Capture System, Delsys Wireless Electromyography (EMG) Sensors, and an AMTI Accusway Force Platform.
1.1 Background

1.1.0 Anatomy of the Knee

The knee is primarily made up of a series of tendons, ligaments, and cartilage. The anterior cruciate ligament (ACL) is one of the four major ligaments in the knee with others being the posterior cruciate ligament, the lateral collateral ligament, and the medial collateral ligament. Both the posterior cruciate ligament (PCL) and ACL control the back and forth motion of the knee (OrthoInfo). More specifically, the ACL provides rotational stability as well the prevention of the tibia sliding in front of the femur. All four ligaments work together to hold the tibia, femur, and fibula together and provide the necessary stability for high impact activities.

Figure 1: Anatomy of the knee and torn ACL

1.1.1 ACL Injuries

ACL injuries commonly occur when someone cuts, jumps, or plants awkwardly in sports such as football, soccer, and basketball in a non-contact manner. Ultimately, this means that the biomechanical threshold of force in the knee is exceeded (Boden). The knee can only withstand up to a certain value that is dependent on the weight of the person. Some of the symptoms include swelling, a pop in the knee when the injury first occurs, pain on the outside and the back
of the knee, and limited movement (Boden). It is also proven the female athletes are more susceptible to this type of injury when compared to male athletes for a variety of reasons. In a study done by Boden et. al, the group states the following reasons as to why females are at a greater risk for an ACL injury: increased knee valgus or abduction moments, generalized joint laxity, ACL size, and the hormonal effects of estrogen on the ACL. In addition, females have a wider pelvis thus causing them to activate the quadriceps muscle group adding more stress to the anterior cruciate ligament.

In addition to the therapy process, there are some other aspects that are important to consider. First, there is the type of surgery which the patient has. There are four types of surgery that are the most common and those include the following: Patellar Tendon Graft (PTG), Hamstring Semitendinosus Graft (HSG) and in some cases allograft and quadriceps tendon graft (QTG). For the patellar tendon graft method, the surgeon takes autograft from the middle-third of the patellar tendon of the patient and uses it as a replacement for the ACL. In those with the hamstring graft method, the surgeon takes autograft from both the semitendinosus and gracilis tendons (OrthoInfo).

Post-surgery, patients with ACL reconstructive surgery tend to experience weakness in the muscles surrounding the knee due to atrophy among other issues. Thus, it is important to take into account muscle activity that someone can exert after having this type of surgery.
1.1.2 Motion Capture System

Motion capture is commonly used to analyze the kinematics and biomechanics of the human body. It could be used to analyze orthopedic joint angles as well as to track the gait of someone. This motion capture system works using six Optitrack (Natural Point, Inc., Corvallis, OR, USA) Flex 13 Cameras and the Optitrack Motive: Tracker program for calibration of the system. The markers for this motion capture analysis are 5 mm reflective markers that send infrared light back to the cameras in this case. Subsequently, the movements of the patient could be tracked. While this study is primarily focused on the lower extremity these markers could just as easily be placed on the upper extremity. For the purposes of this study, the six cameras were aligned in a semi-circle manner as can be seen in figure 3 below. The cameras are thirty degrees apart in groups of three. To be more exact, the distance between cameras one, two, and three are thirty degrees each. The same is true for cameras four, five, and six. However, between cameras three and four there is a sixty degree difference. The reason for this type of setup is to ensure the entire subject area is captured. Each camera runs at 120 frames per second as well as a horizontal field of view of in the stock lens of 56° and a horizontal field of view 42° in the optional lens.
First, the Opitrack Motive: Tracker program is used to both calibrate the camera position as well as the marker positions. This software created rigid bodies from a cluster of at least three or more markers. The rigid bodies were optimized to four markers on each in previous research (Chomack et. al). In the case of this study, the rigid bodies were placed on the thigh, shin (or shank), and foot of each leg. To create these rigid bodies, the markers needed to be in full view of at least two cameras at all times. The markers that were placed on the subject needed to be at similar heights and distances apart so that the model could correctly be assembled. The final rigid body was a moveable stylus. This stylus acts as pointer for joint angles and the length of each body segment. It is important to calibrate the system before each testing session to be sure program determines the correct location of the makers in space. If this is not done in an appropriate manner, the results of the kinematic data may be deemed incorrect. The motion capture data analysis will be discussed at length in a later section in which the Motion Monitor program is described.
1.1.3 Delsys Wireless EMG Sensors

The Delsys Trigno Wireless EMG sensors (Delsys Inc, Natick, MA, USA) can be used to investigate the muscle activity of any particular muscle in the body. The electrodes of 99.9% silver and record a signal of 20 m away. The signal can be recorded at a sampling rate of up to 4000 Hz for as many as eight hours, the length of which the sensors can hold a charge. In this case, the data will be sampled a rate of 1926 Hz. These sensors have an accelerometer and four silver bars that record the electrical activity from the muscles. The sensors send data that is collected back the Trigno Base Station that is connected to the computer via a USB connection. In order to collect accurate recordings, the sensors should be placed at the belly of the muscle and along the muscle fibers (Figure 5).
It is also critical wipe down the skin with an alcohol wipe to remove any dead skin cells or oils that could interfere with the signal.

1.1.4 AMTI Accusway Force Platform

Force platforms can be used in a variety of different manners in both static activities and gait analysis. In the case of static activities, balance control and center of pressure (COP) could be analyzed. The AMTI (AMTI, Boston, MA, USA) Accusway Force Platform has the ability to measure forces and moments in the x, y, and z directions. It is portable, easy to use, and can be used to generate either a digital or analog signal. When recording data, the force platform records at a rate of 100 Hz. The force plate has three Hall-Effect sensors (X, Y, and Z) in each of the four corners of the platform. The analog signal that is produced from the platform is an eight output channels. This type of signal will be used for this analysis and then converted using an A/D converter box that will be discussed in the Motion Monitor section.
1.1.5 S5Ti Treadmill

Using a treadmill is important for any type of exercise ranging from walking to running and in some cases a simulation of walking up or down a hill if the treadmill allows it. In the case of rehabilitation from an ACL injury, getting strength back in the muscles in the knee is vital to improve function in day to day activities. When used in conjunction with a motion capture system it is possible to analyze the gait of someone while walking. Some important factors to consider here are the knee flexion between the healthy and injured legs in the subjects ACL group as well as the control group participants. The gait of a human is usually impacted by compensation due to an injury. For example, someone with ACL injury can be expected to favor one leg over the other causing them to limp.

Another aspect to consider is the fatigue of the muscles surrounding the knee before and after walking on a treadmill. It can be expected that someone with an ACL injury would fatigue faster than someone with no previous knee injuries. One way to analyze this would be with the aforementioned EMG sensors. By recording data of the beginning of the treadmill session and after the session it could be possible to determine whether there is a clear difference between those that have injured their ACL to those that have not.
1.1.6 Motion Monitor

Motion Monitor (Innovative Sports Training, Inc., Chicago, IL) is a comprehensive collection and analysis program with a variety of other functionalities. For this study, it was used to synchronize the data from the aforementioned motion capture system, EMG sensors, and force platform. Based on the rigid bodies that were developed in the Optitrack program, each one is assigned to a segment in the Motion Monitor program. For example, the thigh rigid bodies that
were created translate to the body segment from the hip to the distal end of the femur at the knee. The fibula and tibia segment is created from the rigid bodies that were placed on the shin of both legs. The last rigid bodies is place on the feet. In the Motion Monitor Software, it gives the feet plantar flexion. The stylus is used to point out the joint centers so that a skeletal model of the subject could be properly designed. More specifically, the stylus points to the hip, knee, ankle and second phalynx on the foot. The program is able to figure out the exact proportions of the bone segment based on the height and weight of the subject as well as where the stylus is placed.

In order to integrate the EMG sensors with Motion Monitor, the Delsys Trigno Control Utility program must be running in the background in order to allow the EMG sensors to collect their specific muscle activity data. The data collected from the EMG sensors will be analyzed based on who had an ACL injury and those that are overall healthy. As will be talked about later on, the data includes the following: a high pass filter of 20 Hz, a low pass filter of 350 Hz, and a notch, or bandstop filter, of 60 Hz (Lewek). The EMG sensors can specifically be used to look at weakness of the muscles surrounding the knee which is vital to the rehabilitation process after an ACL reconstructive surgery.

Figure 8: Sample Skeletal Model
The force platform is another aspect that also needs to be translated into the Motion Monitor software. In order to do this, as mentioned earlier, an A/D converter box is necessary. The converter that is used is the USB-1616HS-BNC developed by Measurement Computing (Norton, MA, USA). This box collected data at 100 Hz for all calculations. The eight analog channels from the force platform connect to the device in which the signal is then translated to the digital input. When activated, the Motion Monitor program will begin collecting this force data in conjunction with both the motion capture data and the EMG sensor data. The most important aspect of the Motion Monitor program is that it has the ability to collect all of the data in synchronized matter that makes analysis easier.

1.2 Pilot and Previous Work

Pilot work was done on using this type of software and data analysis to optimize the setup of the markers and cameras in addition to what information can be used for a knee injury. A manual was developed for clinicians during the last academic year at the University of Connecticut by a senior design group for use of these technologies for rehabilitation. A variety of camera positions were investigated, and by trial and error, the optimal position was chosen as discussed earlier. The positioning of the motion capture markers on the thigh, shank, and feet were chosen based on recommendation by the developers of the Motion Monitor in order to create an appropriate skeletal model of the lower extremities. The positioning of the EMG sensors on the specific muscles and force platform in the space was also developed by the group.

The results of specific testing was done using a subject that had torn their ACL as well as someone who was deemed to be a healthy participant. The results of this testing was vital due in order to validate the study for this thesis. The parameters that were investigated in these subjects
were the following: knee flexion, the muscle activity over the trial of squatting, and the center of pressure similar to what was collected in the study for this thesis.

The work that was completed outside of the university is as follows. The first study to mention was done by David R. Bell et. al. and they investigated the different bone graft types that were used during ACL surgery. The different types they investigated were Bone Patellar Tendon graft and hamstring graft similar to what was done in this study. A control was also considered in this study. They used the Motion Monitor system to digitize bony landmarks on the subjects and compared joint angles and moment at the peak knee flexion. It was determined, however, that if the subject had more damage to the knee other than just the torn ACL, there was a significant change in the angles, forces, and moments. This study is significant to consider because the study of this thesis was focused on only people who tore their ACL within the last year and are still undergoing physical or at-home therapy.

A second study investigated was done by Raghav K. Varma et. al. and evaluated people with ACL injuries analyzed whether or not they would be susceptible to osteoarthritis post-surgery by using inclined and flat ground gait analysis. While the prospects of osteoarthritis are not necessarily used in the study, it is important to consider for the purposes of the post-therapy evaluation of each patient and the after effects of the surgery as a whole. Some participants may react differently to the therapy in this thesis, but the goal is to get the patient back to near full strength without any setbacks. Previous studies have also used EMG sensors to analyze the muscle activity of a patient during ACL rehabilitation (Hale, Hart). Some of these studies showed that women are prone to ACL injuries due to the fact that they recruit different muscles in the quadriceps group. While doing squatting or lunges, females use the vastus medialis and vastus
lateralis whereas males tend to use the rectus femoris. It is important to take note of these differences for a few reasons.

1.3 Goals, Specific Aims and Hypotheses

An important metric to investigate is specifically related to how well someone performs post-surgery from an ACL injury. This can be looked from a few different angles. First, there are qualitative measures that are necessary to look at. There are two main measures here: the Tegner scale and the Lysholm scale. The Tegner scale specifically looks into the sports performance level both before and after the injury ranging from no activity at all or competitively performing in sports at a national level. This type of scaling can be used for any type of sports related injury, but it is commonly used in those have injured their ACL during competition. On the other hand, the Lysholm knee scoring scale is specifically used for knee injuries and can be used to track progress over time. It generally evaluates the following performance measures: a limp, whether the person uses a cane or crutches, locking sensation in the knee, giving way sensation from the knee, pain, swelling, climbing stairs, and squatting.

There are also important quantitative measures that could back up these qualitative scales. There are three aspects of the quantitative data the can also be used to evaluate those with ACL injuries: electromyography (EMG) data, kinematic motion capture data, and force platform data. Electromyography is typically defined as electrical activity of muscles using electrodes. In the case of evaluating the ACL injuries and performance, the following muscles should be evaluated: quadriceps, hamstring, and calf. On a more specific scientific level, the vastus lateralis in the quadriceps, the biceps femoris in the hamstring, and the lateral gastrocnemius (Jalali). These muscle groups are vital to analyzing the performance of a human after an ACL injury. The kinematic motion capture data can be used to also investigate those with ACL injuries. This is
mostly based on the exterior biomechanical performance. There are many different aspects, but the important ones to consider here are knee flexion, hip abduction, and how long it may take someone to do a certain activity. The final quantitative measure that could be used for to assess those with ACL injuries is based on a force platform. This type of analysis can be vital to defining the forces and moments in the x, y, and z directions in addition to the center of pressure which can be helpful in defining the balance that the person has while doing a certain activity. This type of analysis is critical to look at the time between reps as well as the difference in force between each rep.

This type of qualitative and quantitative data can lead to the following specific aims and hypotheses for the study.

**Aim 1:** To compare the different surgical techniques (patellar tendon graft and hamstring graft) and the subsequent recovery time for each, as well as the patients’ comfort level post-surgery using the Lysholm and Tegner scales

1. **Hypothesis:** The hamstring graft will prove to be more beneficial than the bone patellar tendon graft based on the technical results gathered during the experiment (Expected technical results are stated in aim 3.)

**Aim 2:** To compare the knee flexion between an individual in the control group and someone that has injured their ACL, while completing the specified and requested physical therapy exercises.

1. **Hypothesis:** We expect to see a greater difference in knee flexion between the injured and healthy leg in the ACL-R subjects.

**Aim 3:** To introduce physical therapy patients to real-time data feedback during the rehabilitative process and to allow them to interact with and react to this information. Specifically, patients will
be provided with immediate quantitative data describing rehab performance, which could also be used by physical therapist to monitor the progress of their patients over time.

1. **Hypothesis:** Subjects who have ACL reconstructive surgery will show different EMG activity (from Delsys EMG Sensors) and balance control (from an AMTI AccuSway Force Platform) compared to the control subjects when performing activities such as sit-to-stand, squatting, and walking exercises. The subject may be able to view and detect any compensatory movements during exercise, which may not necessarily have been seen by the human eye, because of the skeletal model in the Motion Monitor Software displayed during the real-time feedback.

2. **Hypothesis:** While walking at a constant pace of 3.3 miles per hour on the treadmill for approximately 10 minutes, the muscles surrounding the knee (lateral gastrocnemius, biceps femoris, and vastus lateralis) will show more fatigue in subjects with previous ACL injuries, specifically on the injured leg, compared to a control subject. Subsequently, while performing this gait, the hip joint may compensate the most for the fatigued muscles around the knee on the injured leg. However, it should be mentioned that alternative muscles of the body may also compensate to varying degrees during these exercises.

**2.0 Methods**

This study was approved by University of Connecticut Institutional Review Board (IRB) in Storrs, Connecticut (H15-287). The study was completed with the use of an Optitrack Motion Capture System, Delsys Wireless EMG sensors, AMTI Accusway Force Platform, and S5Ti Treadmill from BH Fitness along with Motion Monitor for data collection. The motion capture system will track the movement of the subject during the study. The EMG sensors will measure the muscle activity on the quadriceps, hamstring, and calf on both legs. The force platform will be
used to measure the forces, moments, and center of pressure. The S5Ti Treadmill will be used for gait analysis of the subject.

2.1 Marker Configuration and Motion Capture Analysis

The marker configuration was based on previous research at the University of Connecticut as well as suggestions by the developers of Motion Monitor, Innsport Inc., and Optitrack. The programs work in an optimal manner based on these configurations. Thus, the rigid bodies were created with the use of four reflective markers (9.5 mm) each arranged in a different manner so that they are unique and identifiable by the software. As can be seen in Figure 9 below, the markers on the right leg were placed on the thigh, the shank (or shin) and the foot with a Velcro strap. The markers on the left leg are placed on the same body segments, but instead of Velcro, these were secured to the body using pre-wrap. There is no physical difference between the Velcro strap and use of the pre-wrap. The only difference would be that use of the pre-wrap has a lower overall cost.
Based on this marker configuration, there are a few important measures in that could be used to identify physiological difference between a healthy knee and an injured knee. First, the variables from the motion capture system that could be used are the position, velocity, and acceleration of each body segment. By way of these variables, the knee flexion angle could be precisely calculated by the Motion Monitor software. The point of interest here, however, is the maximum value during the chair squat activity. If someone with a torn ACL was compensating for their injury, they would most likely favor one leg over the other. This could be identified using the maximum knee flexion angle and to find the difference in angle for between each leg. This type of analysis is useful as a way to normalize the data across all of the subjects.

2.2 EMG Placement and Analysis

Surrounding the knee there are three major muscle groups that are impacted post-ACL surgery: the quadriceps, the hamstring, and the calf. More specifically, the part of the muscles that
produce the best signals are generated from the vastus lateralis in the quadriceps group, the biceps femoris in the hamstring, and the lateral gastrocnemius in the calf (M. Jalali). The vastus lateralis originates intertrochanteric line, the linea aspera and the medial supracondylar line, and the insertion is through the quadriceps tend onto the tibial tubercle. Thus, the EMG sensor should be placed over the lateral aspect of the thigh, one handbreadth above the patella bone. The biceps femoris originates from the ischial tuberosity and inserts into the head of the fibula. The sensor is then placed on at the midpoint of a line between the fibula head and the ischial tuberosity. Finally, the lateral gastrocnemius originates from lateral femoral condyle and inserts into the calcaneus through the Achilles tendon. This EMG sensor is then placed one handbreadth below the popliteal crease on the lateral mass of the calf (A.O. Perotto).

![Figure 10: Delsys Trigno Wireless EMG sensors](image)

Electromyography signals also have a potential a significant amount of interference during the recording. Some of these variables include hair and oil or grease on the skin. To account for these variables it is best to wipe down the surface that the sensors are placed on with rubbing alcohol or alcohol wipes. Even still, it is possible that there is noise in the signal and there are certain parameters that need to be taken in order to remove this type of noise. First, there is a notch filter, also known as a band-stop filter, which needs to be incorporated placed on the raw data. This will extract any type of noise that is coming from the electric wiring in the device itself. The frequency of this filter that is applied is 60 Hz. In addition to the notch filter, it is significant to place a high pass and low pass filter, as known as a bandpass filter, on this signal.
from the EMG sensors. The high pass filter removes the low frequency recordings and the low pass filter extracts the high frequency signals which can be interpreted as noise. The high pass filter chosen for each muscle in the study was 20 Hz and the low pass filter of 350 Hz. The filters were chosen based on a previous study done by Lewek et. al. related to ACL injuries.

In addition to the filtering, it is also important to normalize the EMG data so that the participants in the study can be compared in an appropriate manner. One way to do this is to determine the maximum voluntary isometric contractions (MVIC). In most scenarios, this could be used a reference value in determining how much of a muscle a person is using (or activating). However in the case of this study, the maximum dynamic muscle contraction will be calculated and thus used as the reference value. Following the calculation of the maximum value, the peak values for each exercise repetition will be calculated and then averaged together in order to determine how much of the muscle is activated during the exercise (Zeller). The following equation represents how this will be determined:

$$\%\text{Muscle Activated} = \frac{\text{Average of peak values (V)}}{\text{Maximum Dynamic Muscle Contraction (V)}} \times 100 \quad (1)$$

Using equation 1 above, it is possible to determine whether someone with ACL injury has a muscle that is not be used to its full potential. A comparison of the healthy leg versus the injured leg could also prove noteworthy to measure the progress of the participants during the course of the study. Hypothetically, someone should be using close to 100% of a specific muscle most of the time depending on the level of activity if they are a healthy individual.

2.3 Force Platform Analysis

From the force platform, there are a few important measureable factors that can be used to evaluate people with knee injuries. The force platform effectively measures forces and moments
in the x, y, and z directions and these the act as the six measurable variables. The subjects in the study were asked to perform a series of three sitting to standing exercises: 1) Feet shoulder width apart, 2) Left foot in front of the right foot, 3) Right foot in front of the left foot.

Figure 11: Left Foot in front of right foot sitting to standing trial

Figure 12: Normal Sitting to Standing
From this, the maximum force in the y direction ($F_{ymax}$), or ground reaction force, was calculated in order to interpret how much of the body weight, in percentage, that the subjects were exerting on the force platform during a given movement were using during a given trial. The equation for this is listed below:

$$\%Body\ Weight = \frac{\text{Ground Reaction Force Y Direction (N)}}{\text{Body Weight of Subject (N)}} \times 100$$  \hspace{1cm} (2)

Based on this, it is possible to determine whether or not the subjects in the ACL group were exerting as much force during the activity as those in the control group. In addition, it is important to investigate the moments in the x direction to notice if there is any compensation on one leg over the other in the case of the subjects in the ACL group. This data again was normalized to percent body weight as expressed in the following equation:

$$\%Body\ Weight = \frac{\text{Moment z (Nm)}}{\text{Body Weight x Height (Nm)}} \times 100$$  \hspace{1cm} (3)

### 2.4 Subjects and Recruitment

A total of twenty-three subjects were used in this pilot study: fifteen in the control group and eight with ACL reconstructive surgery within the last year. The subjects were all recruited from the University of Connecticut, Storrs Campus and tested in the GP Musculoskeletal Modeling Lab in the Arthur B. Bronwell Building Room 215. The study began in November 2015 and concluded in April 2016. Subjects were recruited for the study in multiple ways. This was done by sending out a message in the UConn Daily Digest email system as well as posting flyers around campus to gain interest in the study. The goal for recruitment in the study was to have 20 participants that have torn their ACL within the last year as well as 20 healthy control subjects. All study participants were between ages of 18 and 23 years of age when the study began both male and female. Subjects in the control group were included in the study if they
were active and had no previous knee injuries or conditions. The inclusion and exclusion for the ACL subjects was as follows.

**Table 1: Reason for inclusion or exclusion for ACL Group**

<table>
<thead>
<tr>
<th>Inclusion Criteria</th>
<th>Exclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ACL reconstruction surgery within the last year</td>
<td>1. If major surgery was required on surrounding ligaments and tendons (PCL, MCL, Meniscus)</td>
</tr>
<tr>
<td>2. Ability to walk as part of the therapy program</td>
<td>2. Other pre-existing knee problems (i.e. arthritis)</td>
</tr>
</tbody>
</table>

Female subjects were between 140 and 160 lbs (± 20 lbs) and between 60 and 66 in (± 3 in) according to the CDC averages (C.D. Fryar) Male subjects were between 150 and 195 lbs (± 15 lbs and between 65 and 72 in (± 3 in) according to CDC averages. Participants were removed from the study if they failed to attend two scheduled appointments without notice.

### 2.5 Subject Testing Protocol

Prior to beginning the study, the participants came to the lab after expressing interest in the study to further discuss it more in depth and signed the IRB approved informed consent document if they were still interested. Subjects were asked to come to the lab two times per month for three months, at their convenience, to complete the testing trials. In total, the subjects visited the lab six times during a 12 week testing period. Each session lasted approximately 45 minutes. The subjects were asked to wear athletic shorts for ease of placing the EMG sensors and motion capture markers. The testing involved the following steps.
1. Prior to beginning the study, the subjects in the ACL group were asked to complete the aforementioned Tegner and Lysholm sheets to get an idea about how their knee is feeling on the day of the first trial. After the final trial they were asked to complete the same form to take note of any qualitative differences.

2. The subjects were asked to remove their shoes if they felt comfortable doing the activities without them.

3. The EMG sensors were placed on the skin using a double-sided sticker provided by Delsys.

4. The motion capture markers were placed on the thigh, shank, and foot using Velcro straps on one leg and pre wrap on the other leg.

5. The subjects were asked to then stand on the AMTI Accusway Force Platform facing the six motion capture cameras that are in the lab.

6. The subjects (both healthy and injured) were asked to perform the following activities in this order:
   a. Chair Squats- 3 sets of 10 repetitions while standing on the force platform
   b. Sit-to-stand- 3 trials of 3 repetitions for each of the following:
      i. Subjects will stand in a normal fashion with feet shoulder width apart
      ii. Subjects will stand with dominant foot in front of the other to measure balance
      iii. Subjects will stand with non-dominant foot in front of the other to measure balance
c. Walking on a treadmill- subjects will walk for 10 minutes at 3.3 miles per hour

7. Activities will be recorded in patient specific folders and saved to the computer.

The experimental test subjects in the ACL group were either in physical therapy or doing at-home exercises to strengthen their knee. All of the activities listed above are typically used in traditional physical therapy rehabilitation programs for ACL injuries, so there was minimal risk posed to the subjects while completing the activities. These activities have specifically be approved by Massachusetts General Hospital for ACL rehabilitation. Prior to beginning the study, the participants recruited for the ACL group were asked if they have performed these activities in their programs to ensure they would feel comfortable during the trials.

2.6 Filtering

As mentioned earlier in the EMG analysis section, it is necessary to filter all electromyography data to remove any noise in the signal as well as any motion artifact. The filtering was done using the Motion Monitor software which has the capabilities to manually input a specific filter type for each specific sensor. Typically, EMG signal occurs in a range of 5 Hz to 400 Hz. In case of this study, the low pass filter was chosen to be 350 Hz and a high pass filter of 20 Hz (Lewek). When analyzing knee injuries, specifically ACL injuries, this are common filter types. This type of filtering made the signal clearer and sharper as well as the shift the data to be on the x-axis of the graph. In addition to the EMG data, the motion capture and force platform data was filtered using a Butterworth filter of 20 Hz.
2.7 Peak Detection for EMG Signal

In addition to the EMG data, the motion capture and force platform data was filtered using a Butterworth filter of 20 Hz. The sampling rate for both of these devices were comparable and produced little noise in their signal, thus little filtering was required.

There were two programs that were written to analyze the data that was exported from the Motion Monitor software. During each of the trials, it was important to identify the maximum dynamic contraction as well the additional peaks to calculate the average during each specific activity. First, a program was written in C++ to analyze the data from the chair squat activity and the regular sitting to standing activity. To find the peaks for a particular muscle (vastus lateralis,
biceps femoris, and lateral gastrocnemius), the average of all the data points was calculated. The data was iterated a second time, with the maximum value found between frames, or time points, where the value was below average being a candidate peak. Each activity had an expected number of peaks, 10 for the chair squat and 6 for the sit to stand activity. The list of candidate peaks was sorted highest to lowest, and the first $n$ candidate peaks were considered the peaks, where $n$ is the expected number of peaks for the activity. The average of the peaks, as well as the maximum peak, were the outputted in a .csv file.

Second, a LabVIEW program was designed to sort the treadmill data from the Motion Monitor software. The program acted a method of peak detection and selection for the EMG analysis. The average of the peaks during the activity could be also be defined with this program. One output of the LabVIEW program was exactly this. It was important to identify these peaks so that the percentage of muscle contraction could be calculated for each subject during each trial. The program itself contains a series of Boolean controls in which the user can pick the specific peaks that they are interested in. In some data files, there were smaller peak values that could be misinterpreted as a peak by an automated program, hence the reason for the Boolean controls. The average peak value is detected based on these controls.

### 2.8 Experimental Setup

The subjects were placed in the center of the camera space, and it was subsequently translated to the virtual space created by the motion capture software. There were two configurations that were used for this study, one with the force platform and the other with the treadmill. The cameras were setup in a semicircle each approximately ten feet from the center of the force platform where the subject was standing and thirty degrees apart from one another. As
can be seen in the figure below, the subject is standing on the AMTI Accusway Platform ready to perform either the chair squat or the sitting to standing activity.

![Experimental Setup with Force Platform](image1)

Figure 15: Experimental Setup with Force Platform

The second setup for the study was with the treadmill. The participants were walking on the treadmill with the same camera configuration with the force platform removed from the setup as can be seen in the figure below.

![Experimental Setup with Treadmill](image2)

Figure 16: Experimental Setup with Treadmill
2.9 Validation

The study focuses mainly on those with ACL injuries currently in the rehabilitation process or still doing at-home exercises. The reason for this study is to validate the different surgical techniques and determine which, if any, is more beneficial than the other. These techniques, of course, are hamstring tendon graft and bone patellar tendon graft as mentioned earlier. With this study, the hope is to be able to determine which type of reconstruction surgery aids or improves the rehabilitative process. Currently, there is some controversy about which type of graft is the most beneficial for use in the ACL reconstruction surgery. This research will potentially clarify this debate and provide doctors and surgeons with a better understanding of patient outcomes after ACL surgery.

Additionally, this study will also validate whether or not the aforementioned technology could be used in a physical therapy setting. In its own way, the patients will be exposed to real-time feedback that can allow them to interact with and reach with this information on the spot. Specifically the patients will be provided with immediate quantitative data describing rehab performance, which could also be used by physical therapists to monitor the progress of their patients over time.

3.0 Results

3.1 Subject Demographics

This study was approved by the Institutional Review Board (IRB) at the University of Connecticut and all participants were required sign an informed consent form to participate. A total of 33 subjects were enrolled in this study: 21 subjects in the control group and 12 subjects in
the ACL reconstruction (ACL-R) group as seen in the table 2 below. The average age of both groups is 19.45±0.94 years. The recruited age range was 18-23 years old, however, age range in the study was only 18-21 years. Of the participants in the ACL-R group, the subjects ranged from 2-10 months out from surgery at the beginning of the study in January 2016. As mentioned earlier, typical recovery time from this type of injury is 9-12 months so these subjects were either still in physical therapy or doing at-home exercises.

Table 2: Patient Demographics

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>ACL-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>19.19±0.87</td>
<td>19.92±0.90</td>
</tr>
<tr>
<td>Height (in)</td>
<td>67.60±3.95</td>
<td>66.71±3.36</td>
</tr>
<tr>
<td>Weight (lbs)</td>
<td>151.90±28.75</td>
<td>148.75±26.29</td>
</tr>
<tr>
<td>Sex Ratio (M/F)</td>
<td>10/11</td>
<td>6/6</td>
</tr>
</tbody>
</table>

*All values are expressed in mean±SD

Before the study began, there were 10 participants that were lost due to follow-up: six in the control group and four in the ACL-R group. After the study began, there were only two subjects did not complete the full testing protocol of six trials. The results from these two participants were not included in the final analysis which consisted of 21 total participants. Each participant was evaluated once every two weeks to monitor progress, if any, during the course of the study.

3.2 Qualitative Data

As mentioned in the methods section, the subjects in the ACL group were evaluated before and after the study with both the Tegner and Lysholm scales before and after the study. More specifically, the Tegner addresses the sports activity level from little to no activity at level 0 to competitive sports at a national elite rank at level 10 before the surgery and after the surgery. The
subjects subjectively filled this out at the beginning of the study and at the end. The Lysholm scale address common complaints with any type of knee injury that include whether person has a limp, uses a cane or crutches, a locking sensation in the knee, a giving way sensation in the knee, pain, swelling, climbing stairs, squatting. Each category has its own score and these are also summed to get the total of 1000. It could be expected that the subjects still recovering should have an improved score after completion of the study as they continued with their own physical therapy.

<table>
<thead>
<tr>
<th>Table 3: Tegner and Lysholm Scoring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tegner Before Injury</strong>&lt;br&gt;(Out of 10)</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td><strong>Before Study</strong></td>
</tr>
<tr>
<td><strong>After Study</strong></td>
</tr>
</tbody>
</table>

As can be seen in the table above, there was not a significant difference before and after the study. In fact, most subjects reported similar if not equal values for each category using both scales. It is interesting to note that these were filled out on different days more than three months apart. This shows that psychologically the participants felt that they only slightly improved.

### 3.3 Comparison of ACL Surgical Techniques

As mentioned earlier, there is some controversy between which type of ACL surgical techniques is more beneficial. This could be investigated from a few different angles. First, the results from the motion capture yield important kinematic data that can reflect such a difference. Specifically, from the motion capture system there are a total of nine variables that are produced based on the position, velocity, and acceleration from each of the markers located on the subject. In addition to the motion capture data, there were six variables were produced from the EMG
sensors from each of the different muscles and six from the force platform data, forces and moments in the x, y, and z directions.

3.3.1 Kinematic Analysis

There are a variety of ways to analyze the kinematic data one of these involves a comparison of the knee flexion data over the course of the six different trials with a comparison done primarily between the two groups: control vs. ACL-R. This variable is significant due to the fact that those post-ACL surgery may be favoring one leg over the other. In addition to this overall comparison, ACL-R subjects were compared based on the type of surgery they had to see if the data provides any evidence as to what shows greater improvement. The analysis was done by finding the knee flexion angle in the Motion Monitor program and taking the absolute value of the difference between both of the legs in the participants. It was hypothesized that the control subjects would have a similar knee flexion angle given that they are believed to healthy, active individuals. Also, it was believed that the hamstring tendon graft group would perform better than those with patellar tendon graft surgery in the ACL-R group due to the surgery type.
For this analysis, the average maximum angle of knee flexion was found for the each chair squat activity that the subjects performed. The first comparison that was drawn was over the course of the study between the control group and the ACL-R group to track the progress over time.

The activity used in this part of the analysis of was the chair squat. From the graph above, it was clear that the subjects in the control group had a relatively constant degree difference in knee flexion that varied between four degrees and five degrees. On the other hand, the ACL group showed progress over the course of the six trials and regressed to the control group knee flexion data. Due to the small sample size, in the ACL group, there were was a high variability in the results as can be seen in the table 4 below.

Table 4: Difference in Knee Flexion (ACL-R Group)

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Range (in degrees)</th>
<th>Average ± Standard Deviation (in degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.99</td>
<td>7.42 ± 4.21</td>
</tr>
<tr>
<td>2</td>
<td>13.44</td>
<td>5.95 ± 4.47</td>
</tr>
</tbody>
</table>
While visually from the graph it appears that there is a difference between the groups, there was no statistically significant difference between the groups over the course of the six trials at the 0.05 level after performing a two-tailed $t$-test.

Table 5: Comparison of Between Control and ACL-R Group Knee Flexion

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Control Group</th>
<th>ACL-R Group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In Degrees</td>
<td>In Degrees</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.64 ± 4.26</td>
<td>7.42 ± 4.21</td>
<td>0.21</td>
</tr>
<tr>
<td>2</td>
<td>4.26 ± 4.84</td>
<td>5.95 ± 4.47</td>
<td>0.46</td>
</tr>
<tr>
<td>3</td>
<td>4.81 ± 3.37</td>
<td>7.03 ± 3.67</td>
<td>0.23</td>
</tr>
<tr>
<td>4</td>
<td>4.91 ± 2.80</td>
<td>6.46 ± 4.55</td>
<td>0.46</td>
</tr>
<tr>
<td>5</td>
<td>3.86 ± 2.38</td>
<td>6.26 ± 4.69</td>
<td>0.28</td>
</tr>
<tr>
<td>6</td>
<td>4.75 ± 3.08</td>
<td>3.93 ± 3.18</td>
<td>0.60</td>
</tr>
</tbody>
</table>

While there is a large variability it is still possible to send a trend in the results of those in the ACL group. A larger study would be useful to measure the trends in the knee flexion data. These results specifically address one of the goals to track progress over time. The feasibility to use this technology and accomplish this goals was successful.

In addition, to a comparison between the two groups, it was important to compare the differences, if any, between those in the ACL-R group with the different types of surgery as this
was the primary goal of the study. The knee flexion degree average difference was calculated in the same way as above. It is important to take note of the differences because this could potentially give orthopedic surgeons a new way to approach the surgical treatments of their patients with ACL injuries. The number of subjects evaluated in this part of the analysis was five: three with the hamstring graft surgery and two with the patellar tendon surgery. The sample size decreased due to the drop out of two participants from the study, one from the hamstring group and one from the patellar group.

![ACL Hamstring Group](image)

*Figure 18: Hamstring Tendon Group Change in Knee Flexion vs. Time*
Figure 19: Patellar Tendon Group Change in Knee Flexion vs. Time

Table 6: Comparison of ACL Groups Difference in Knee Flexion

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Trial 6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Units</strong></td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
</tr>
<tr>
<td><strong>Hamstring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subject 1</td>
<td>7.48±1.06</td>
<td>5.05±0.14</td>
<td>4.26±0.95</td>
<td>1.05±1.14</td>
<td>5.43±4.60</td>
<td>0.78±0.69</td>
</tr>
<tr>
<td>Subject 2</td>
<td>8.07±1.98</td>
<td>13.87±1.37</td>
<td>6.88±1.83</td>
<td>10.79±2.13</td>
<td>10.58±3.04</td>
<td>3.99±4.26</td>
</tr>
<tr>
<td>Subject 3</td>
<td>10.41±1.50</td>
<td>3.59±4.91</td>
<td>3.23±2.03</td>
<td>3.67±1.33</td>
<td>13.17±2.30</td>
<td>1.55±0.43</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>2.93</td>
<td><strong>10.28</strong></td>
<td>3.65</td>
<td>9.74</td>
<td>7.74</td>
<td>3.21</td>
</tr>
<tr>
<td><strong>Patellar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subject 1</td>
<td>0.86±0.72</td>
<td>0.43±0.35</td>
<td>6.45±1.00</td>
<td>3.11±1.54</td>
<td>3.56±1.75</td>
<td>3.28±1.94</td>
</tr>
<tr>
<td>Subject 2</td>
<td>4.84±2.23</td>
<td>6.50±3.44</td>
<td>7.65±1.13</td>
<td>7.82±5.40</td>
<td>4.10±2.41</td>
<td>9.80±0.97</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>3.98</td>
<td>6.07</td>
<td>1.19</td>
<td>4.71</td>
<td>0.54</td>
<td><strong>6.53</strong></td>
</tr>
</tbody>
</table>
Table 7: Control Group Difference in Knee Flexion

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Trial 4</th>
<th>Trial 5</th>
<th>Trial 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
<td>degrees</td>
</tr>
<tr>
<td>Maximum</td>
<td>13.13</td>
<td>16.15</td>
<td>11.74</td>
<td>10.46</td>
<td>8.64</td>
<td>10.19</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.28</td>
<td>0.38</td>
<td>1.47</td>
<td>0.90</td>
<td>1.09</td>
<td>0.54</td>
</tr>
<tr>
<td>Range</td>
<td>12.84</td>
<td><strong>15.77</strong></td>
<td>10.28</td>
<td>9.56</td>
<td>7.54</td>
<td>9.65</td>
</tr>
</tbody>
</table>

From the data, in the above graphs and tables, there are a few noticeable trends related to the differences between the ACL Hamstring group and the ACL Patellar group in addition to the control group. Because of the small number of participants, the groups were compared based on the range of values. By looking at figures 18 and 19 as well as table 6, there is a clear difference between the different surgical techniques. Each line in the graphs represents a different subject within the ACL group. Over time, the subjects in the hamstring group showed improved knee flexion to the point where there was almost no difference between either legs. On the other hand, the patellar tendon subjects showed more of a variation in knee flexion during the chair squatting activity. It is important to take into consideration here, that the patellar tendon group of subjects may be compensating for their injuries. One way to look at this would be investigating the difference in velocity of the thigh segment between a subject in the control group, a subject in the ACL hamstring group, and a subject in the ACL patellar group. From preliminary calculations of this variable, there is no clear difference between these subjects.

In the short term, it appears that the patellar tendon graft has better outcomes initially. However, the hamstring tendon graft has potentially better outcomes in the long run. This could better be explained by a longer longitudinal study that investigates subjects immediately following
surgery to the point where the physical therapists and doctors deem they have been cleared full participation in sports. Similarly, when looking at the data for the control group, it is apparent that they are fairly consistent over the course of the study as would be expected. The subjects in the control group also have a lower degree of variability between the subjects.

3.3.2 Force Platform Analysis

Using the force platform to analyze the differences in those with ACL injuries is another important factor. Given that it is able to determine the ground reaction forces during either the chair squat or sitting to standing activities, it is possible to determine with whether those in the ACL group are putting more force on their uninjured knee. In the control group, it could be expected that the resulting force will be similar in both legs during the activities. The percent body weight used during the sitting to standing exercises was calculated here. The seat of the chair used in the study was approximately 24 inches from the floor and was used across all trials for all subjects. The constant height of the chair was kept uniform to normalize the data across all of the subjects.

The first part of analysis deals with the results generated from the regular sitting to standing trials with feet of the subject shoulder width apart. The weight of the subjects were first converted from pounds to Newtons and then equation 2 was applied from above to generate the percent body weight for each subject. The subjects could then be compared based on this percentage over the course of the study.

Table 8: Normal Sit-to-Stand in percent body weight (ACL-R Group)

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Range (in %)</th>
<th>Average ± Standard Deviation (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45.61</td>
<td>97.34 ± 19.06</td>
</tr>
<tr>
<td>2</td>
<td>46.48</td>
<td>111.41 ± 17.43</td>
</tr>
</tbody>
</table>
As can be seen in the table above, the results are variable in the ACL-R group when determining the percent body weight that is used in the particular exercise. Interestingly enough, the subjects used on average 103.32% percent body weight over the course of the study while performing this specific exercise. As was the case with the kinematic data, it is important to compare those with the different types of ACL injuries.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>46.27</td>
<td>102.05± 15.14</td>
</tr>
<tr>
<td>4</td>
<td>27.77</td>
<td>110.19 ± 11.07</td>
</tr>
<tr>
<td>5</td>
<td>42.77</td>
<td>102.04 ± 16.57</td>
</tr>
<tr>
<td>6</td>
<td>30.87</td>
<td>96.88 ± 11.36</td>
</tr>
</tbody>
</table>

*Figure 20: Ground Reaction Force progress over time (ACL Hamstring Tendon Graft)*
From the graph of the results it is clear that there are minor differences between the two different surgical techniques. By investigating the ground reaction forces, it may be possible to determine which group has an improved ground force over the course of the study approaching approximately 100%. A two-tailed t-test was performed to compare the subjects between each of the six trials and only trial five (p=0.04) proved to be statistically different between the two types of surgical techniques. In addition, there was comparison drawn between the control group and the ACL-R which also proved no significant difference between the groups over the course of the six trials.

**Table 9: Ground Reaction Forces (Control vs. ACL-R)**

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>Control Group</th>
<th>ACL-R Group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In %</td>
<td>In %</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>104.44 ± 16.03</td>
<td>97.34 ± 19.06</td>
<td>0.45</td>
</tr>
<tr>
<td>2</td>
<td>109.16 ± 20.90</td>
<td>111.41 ± 17.43</td>
<td>0.86</td>
</tr>
<tr>
<td>3</td>
<td>104.07 ± 16.67</td>
<td>102.05 ± 15.14</td>
<td>0.79</td>
</tr>
<tr>
<td>4</td>
<td>113.50 ± 21.28</td>
<td>110.19 ± 11.07</td>
<td>0.64</td>
</tr>
</tbody>
</table>
In addition to the ground reaction forces, it is also vital to investigate the moments in the $z$-direction to see if there is any compensation for the subjects in the ACL-R group by favoring one leg over the other (injured leg vs. healthy leg). By looking at the $z$-direction, physiologically this type of analysis looks into the mediolateral plane. When investigating the subjects in with the different surgical techniques, the following results were discovered.

![Figure 22: Moment Z-Direction for Normal Sit-to-Stand Activity](image)

The graph above shows the changes in data from trial to trial when comparing the entire control group to the whole ACL-R group. It is evident that there no significant difference between the groups as they follow the same trend ($p=0.78$). It is more interesting to look closer at the ACL-R group and compare the surgical techniques.
When comparing the subjects in the ACL-R group there are some interesting results that were produced. First, over the course of the study, there was no significant difference between the subjects over the course of the six trials (p=0.95). However, the trends that each of the subject groups follow is quite different and the reasoning for this will be discussed later on in the discussion. In addition to evaluating the normal sit-to-stand technique, the subjects were asked to place both of their feet in a line heel to toe first with the left foot in front and second with the right
foot in front. The figure of the models below the show the activities that the subjects were asked to perform in this case.

![Figure 25: Sit-to-Stand Models](image)

The subjects in the ACL-R with the different surgical techniques were evaluated here to investigate their movement in the mediolateral plane with push off leg being both the healthy leg and the injured leg. The differences are described in the table below.

*Table 10: ACL Comparison for Heel to Toe Sit-to-Stand Technique*

<table>
<thead>
<tr>
<th>Units</th>
<th>Push off Injured Leg</th>
<th>Push off Healthy Leg</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamstring</td>
<td>percent</td>
<td>percent</td>
<td>percent</td>
</tr>
<tr>
<td>Subject 1</td>
<td>8.03±1.08</td>
<td>8.82±1.99</td>
<td>0.79</td>
</tr>
<tr>
<td>Subject 2</td>
<td>7.44±1.41</td>
<td>7.43±1.73</td>
<td>-0.02</td>
</tr>
<tr>
<td>Subject 3</td>
<td>5.11±0.64</td>
<td>6.04±1.70</td>
<td>0.93</td>
</tr>
<tr>
<td>Patellar</td>
<td>percent</td>
<td>percent</td>
<td>percent</td>
</tr>
<tr>
<td>Subject 1</td>
<td>9.34±1.99</td>
<td>9.08±1.96</td>
<td>-0.26</td>
</tr>
<tr>
<td>Subject 2</td>
<td>5.63±2.39</td>
<td>6.69±1.71</td>
<td>1.06</td>
</tr>
</tbody>
</table>
The subjects in the ACL-R group were compared and divided by the surgical techniques once again. The data was not statistically significant, however, in three out of the five subjects the moment in the z-direction was a higher percentage of body weight. This could explain a few the movements of the subjects in the mediolateral plane. The reasoning will be discussed in a later section.

3.3.3 EMG Sub-Analysis

Data from the EMG sensors were collected during all of the activities in the study. The analysis of the EMG data is quite complex, so the data was taken from the final three trials for each of the 21 participants that were analyzed. In addition, the data recorded in the final three trial was more reliable based on the placement of the sensors. The comparison of maximum dynamic contraction was done for the control group against the ACL group. Another comparison was done to investigate the differences between the surgical types. By using the LabVIEW and C++ program, the peaks were able to be chosen specifically and averaged. The programs were used for the analysis of the chair squatting activity and the sitting-to-standing activity for difference between each muscle and the treadmill data was to analyze weakness or fatigue or possible strengthening. The hypothesis across all trials was believed to be that those in the hamstring group would show a greater difference in average muscle activation using the formula stated above.

The first comparison that was done took the average difference for each muscle over the trials for each of subjects. It is important to investigate muscle by muscle to look at any potential differences between the control group and those with the different surgical techniques in the ACL-R group. The percentage of activation was calculated based on the average of the peaks in the specific activities as well as maximum dynamic contraction detected during the specific activity.
As mentioned earlier, this was a way to normalize the data across different trials as well as the different subjects.

3.3.3.1 Chair Squat EMG Analysis

The first part of the analysis uses the chair squat activity and compares the various muscles between each of the groups. Beginning with the vastus lateralis muscle in the quadriceps group, both the control group and the ACL-R group show some interesting results. The subjects in the control group have a percent difference in activation that ranges from 6.56% to 18.36% over the course of the three sessions. The mean percent difference in activation was 10.52% with a standard deviation of 3.61%. Meanwhile in the ACL group, the percent difference in activation ranged from 7.65% to 21.35% with a mean of 13.08% and standard deviation of 5.27%. A two-tailed test was performed on this data to check for statistically significance and it proved that there was no significant difference between the control group and the ACL-R group at the alpha level of 0.05 (p=0.31).

![Figure 26: Vastus Lateralis Activation during Chair Squat (Control Group)](image-url)
In the figure above, each subject in the control group is represented by a different bar with error bars included that represent the standard deviation of the subjects over the trials. Interestingly, the subjects, in general, with a lower difference in muscle activation for the vastus lateralis were the female subjects. This could be explained for a few reasons. First, the male subjects tended to have larger quadriceps muscles. Additionally, the male subjects exercise more frequently than the female subjects thus they could potentially favor one leg over the other creating the difference in the graph above. Also, something to consider is that overall voltage of muscle activation was higher in the male subjects as well. After performing a two-tail t-test with an alpha of 0.05, it was determined that there was not a statistically significant difference between the male subjects and the female subjects in the control group (p=0.14).

![Vastus Lateralis EMG ACL-R Group](image)

*Figure 27: Vastus Lateralis Activation during Chair Squat (ACL Group)*

Again, it was important to compare those within the ACL group to explore any potential differences between the surgical techniques. As can be seen in Figure 29 below, the subjects with the patellar tendon graft had a lower percent difference in activation than the three subjects with
the hamstring tendon graft in the vastus lateralis. There is still no statistical significance between the two ACL surgical types at the 0.05 level (p=0.12).

Figure 28: Vastus Lateralis Activation during Chair Squat (Hamstring Tendon ACL Group)

The next part of the analysis follows the same procedure as above except for the biceps femoris and the lateral gastrocnemius. It is important to take into account these muscles as well as
they could provide more insight into the how the subjects were performing during the trials for the chair squat activity.

![Figure 30: Control Group Biceps Femoris Activation during Chair Squat](image)

The first comparison that was done was of the fifteen subjects within the control group. As can be seen in figure 30 above, the subjects had a variable range of difference in the average biceps femoris activation between the two legs. The mean average difference between each leg was 14.88% with a standard deviation of 5.76%. A two-tailed t-test was performed to test for statistical significance between the males and females within the control group. It was proven that there was no significance in this case (p=0.56).
The next comparison that was drawn was the difference between the control group and the six subjects in the ACL-R group. The subjects in the ACL group had an activity difference that ranged from 9.15% to 18.94% with a mean of 13.67% and standard deviation of 3.25%. Using the same procedure, a two-tailed t-test was performed on the samples of each group. The test revealed that there was no statistically significant difference between the biceps femoris activity (p=0.55).
In this case, it is more interesting to dive deeper into the ACL-R group and how the different surgical techniques (hamstring and patellar tendon grafts) could compare to one another. This muscle is particularly interesting because it could be hypothesized that those with the hamstring reconstruction will have a larger difference between each leg than those with the patellar reconstruction. In the two figures above, the subjects are split between the types of surgery. As expected the subjects with the patellar tendon reconstruction had less of a difference between each leg than those with the hamstring reconstruction. However, this such difference was not statistically significant through use of a two-tailed t-test (p=0.19).

The last muscle that was tested was the lateral gastrocnemius during the chair squat activity. The same difference in activation between each leg over the final three trials was calculated as it previously had for the other muscles. The range for the control group 9.08% to 27.33% with a mean of 17.62% and a standard deviation of 5.61%. Similarly, the ACL-R group had a range of 6.62% to 33.64% with a mean of 16.41% and a standard deviation of 9.63%. A two-tailed t-test was performed to compare the two groups and it was determined that there was no statistically significant difference (p=0.78). The subjects in the control group were also tested to
compare the female subjects and male subjects. When the two-tailed t-test was performed, it revealed that there was no statistical significance at the alpha level of 0.05 between the two subjects samples (p=0.84).

Figure 34: Control Group Lateral Gastrocnemius Activation during Chair Squat

Figure 35: ACL-R Group Lateral Gastrocnemius Activation during Chair Squat
Figures 36 and 37 above represent the specific subjects in the ACL-R group with the two common ACL surgical types. The results from this muscle are variable and do not clearly show a preference for one surgical technique over the other. The two groups were also not statistically significant (p=0.64).
3.3.3.2 Sit-to-Stand Exercise EMG Analysis

The second activity that the subjects were asked to perform was a sitting to standing exercise with both feet shoulder width apart. The subjects were asked perform three sets of three repetitions of the sitting to standing motion ending with the subject in the seated position. The subjects would be expected to have a total of six peaks values for each muscle each of which were averaged and normalized to the maximum value recorded during the trials. The six peaks that were detected and averaged using the C++ code. The same average difference between the legs was found just like the chair squat activity to determine if there was a significant difference between the subjects in the control group and the ACL-R group. Also, the data was checked between the subjects with the different surgical techniques in the ACL-R group.

The first muscle to be analyzed, as in the last section, is the vastus lateralis. The subjects in the control group for this exercise had a difference in vastus lateralis activation that ranged from 7.09% to 14.54% with a mean of 11.14% and standard deviation 3.63%. The subjects in the ACL-R group had a difference in vastus lateralis activity during the sit-to-stand exercise that ranged from 11.33% to 18.60% with a mean of 13.48% and standard deviation of 2.76%. Interestingly, the subjects in the control group had a more variable difference. However, the difference between the two groups was not statistically significant (p=0.14) after a two-tailed t-test. A comparison of the female subjects and male subjects in the control group was also conducted also yielding a significant difference (p=0.02).
Figure 38: Vastus Lateralis Activation during Sit-to-Stand Activity (Control Group)

Figure 39: Vastus Lateralis Activation during Sit-to-Stand Activity (ACL-R Group)
As in the previous sections, the subjects in the ACL group were compared based on the type of surgery they had. In the two figures above (Figures 40 and 41), the results of the hamstring tendon graft group and patellar tendon graft group show that there was no apparent difference as the vastus lateralis data is similar across the groups. The five subjects were tested for statistical
significance with a two-tailed t-test and it was determined that there was no statistical significance (p=0.69) between the two surgical techniques proving this muscle inconclusive for this activity.

The next muscle to be investigated was the biceps femoris for the sit-to-stand activity. The subjects were first compared between the control group and the ACL-R group. The subjects in the control group had a difference in biceps femoris activity that ranged from 6.18% to 22.28% with a mean of 12.06% and standard deviation of 4.09%. The subjects in the ACL-R group had a range in difference of biceps femoris activity from 7.24% to 14.37% with a mean of 11.75% and standard deviation of 2.84%. However, these two groups were not statistically significant (p=0.84). The male and female subjects in the control group were also compared and it appeared that there was no statistical significance (p=0.74).

![Biceps Femoris EMG Control Group](image-url)

*Figure 42: Biceps Femoris Activation during Sit-to-Stand Activity (Control Group)*
Figure 43: Biceps Femoris Activation during Sit-to-Stand Activity (ACL-R Group)

Figure 44: Biceps Femoris Activation during Sit-to-Stand Activity (Hamstring Tendon ACL Group)
In this case, there are some interesting results related to the comparison between the two types of ACL surgery. As can be hypothesized, one could except that the subjects in the ACL-R group with hamstring tendon reconstruction would have a greater difference between each leg (injured vs. healthy) than those with the patellar tendon graft. This was proven to be the case. The subjects were compared with the two-tail t-test and it was determined that the difference was not statistically significant (p=0.81). However, the subjects in with the patellar tendon graft still performed better on average. This could be explained for a few reasons. One and probably the most important reason being that the subjects with the hamstring reconstruction would be expected to have a weaker hamstring in the injured leg. Thus, it resulted in a greater difference between the two legs as reported in the graphs above. In the patellar tendon graft surgery, the hamstring is not impacted by the surgery. A large difference should not be expected and this was confirmed based on the data collected and shown in Figure 45.

The final muscle to be analyzed for the sit-to-stand activity is the lateral gastrocnemius. The subjects in the control group and ACL-R group were first compared against one another to
test if the EMG data was significantly different using a two-tailed t-test. The subjects in the control group had an average difference between their legs for the lateral gastrocnemius that ranged from 8.38% to 19.45% with a mean of 14.87% and standard deviation of 2.75%. The subjects in the ACL-R group had a range of 9.97% to 21.64%. Between the two groups, there was no statistical significance after performing a two-tailed t-test at an alpha of 0.05 (p=0.19). Additionally, the subjects in the control group were compared between males and females and there was not a significant difference (p=0.89).

Figure 46: Lateral Gastrocnemius Activation during Sit-to-Stand Activity (Control Group)
Figure 47: Lateral Gastrocnemius Activation during Sit-to-Stand Activity (ACL-R Group)

Figure 48: Lateral Gastrocnemius Activation during Sit-to-Stand Activity (Hamstring Tendon ACL Group)
Next, the subjects in the ACL-R group were compared to see if there was any significant difference between the different surgical techniques as had been done in the prior sections. By looking the figures above, there appears to be minor differences between the different types of surgery. After performing a two-tailed t-test, it was revealed there was no significance in the two subjects groups (p=0.78).

3.3.3.3 Treadmill EMG Analysis

The last part of the EMG analysis involves using the data collected from the treadmill exercise. The subjects walked on the treadmill for 10 minutes and 3.3 miles per hour, with data collection occurring at the beginning in the first 10 seconds and final 10 seconds. By recording the data at the beginning and the end it could be possible to determine fatigue of the muscles. In the case of all the numbers that were reported, a positive number indicates muscle function decrease, whereas a negative number indicates muscle activation increase. A decrease in muscle function will be qualified as a fatigue in this analysis. The difference in muscle function was found by
taking each individual muscle (right and left for each) and subtracting the initial muscle activation and the final, post-exercise muscle activation from one another for all of the trials.

The first comparison that was drawn was between the subjects in the control group compared to those in the ACL-R group. The table below shows the mean differences in muscle activation that was recorded during the treadmill exercise.

*Table 11: Treadmill Mean Muscle Activation Difference Before and After Exercise (Control vs. ACL-R)*

<table>
<thead>
<tr>
<th></th>
<th>Control (%)</th>
<th>ACL-R (%)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Vastus Lateralis</td>
<td>1.71 ± 11.85</td>
<td>1.87 ± 16.78</td>
<td>0.98</td>
</tr>
<tr>
<td>Left Vastus Lateralis</td>
<td>4.99 ± 12.12</td>
<td>-9.06 ± 6.37</td>
<td>0.04</td>
</tr>
<tr>
<td>Right Biceps Femoris</td>
<td>1.32 ± 10.03</td>
<td>-5.07 ± 9.48</td>
<td>0.19</td>
</tr>
<tr>
<td>Left Biceps Femoris</td>
<td>-9.36 ± 9.52</td>
<td>0.83 ± 5.58</td>
<td>0.05</td>
</tr>
<tr>
<td>Right Lateral Gastrocnemius</td>
<td>2.71 ± 9.88</td>
<td>-0.52 ± 2.79</td>
<td>0.26</td>
</tr>
<tr>
<td>Left Lateral Gastrocnemius</td>
<td>0.38 ± 6.64</td>
<td>0.51 ± 14.98</td>
<td>0.94</td>
</tr>
</tbody>
</table>

The groups were tested for statistical significance using a two-tailed t-test with an alpha value of 0.05 as similarly done in the previous results sections. There were some interesting results that were discovered when analyzing this data. It was determined that there was a statistical significance between the groups in the left vastus lateralis (p=0.04) as well as the left biceps femoris (p=0.05). This results seems plausible due to the fact the five out of the six ACL subjects tore the ACL in their left leg. Some possible compensation could also be detected here as there was strengthening of the left vastus lateralis but fatigue in left biceps femoris. This is one result that could be expected over the 10 minute exercise period.

The next comparison was between the different surgical techniques in the ACL-R group. It was important to investigate the different surgical techniques because it is certainly possible that the subjects will have different fatigue or strengthening patterns based on the surgery. The differences between the two subjects with the patellar tendon graft and three subjects with the hamstring tendon graft are expressed in the table below.
Table 12: Treadmill Mean Muscle Activation Difference Before and After Exercise (Patellar Graft vs. Hamstring Graft)

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Patellar Tendon Graft (%)</th>
<th>Hamstring Tendon Graft (%)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Vastus Lateralis</td>
<td>15.72 ± 12.57</td>
<td>-6.48 ± 18.03</td>
<td>0.20</td>
</tr>
<tr>
<td>Left Vastus Lateralis</td>
<td>-7.71 ± 8.25</td>
<td>-11.37 ± 6.98</td>
<td>0.66</td>
</tr>
<tr>
<td>Right Biceps Femoris</td>
<td>-8.28 ± 17.32</td>
<td>-0.53 ± 2.74</td>
<td>0.64</td>
</tr>
<tr>
<td>Left Biceps Femoris</td>
<td>-2.14 ± 10.50</td>
<td>3.17 ± 2.23</td>
<td>0.61</td>
</tr>
<tr>
<td>Right Lateral Gastrocnemius</td>
<td>-1.75 ± 1.25</td>
<td>-0.95 ± 3.15</td>
<td>0.71</td>
</tr>
<tr>
<td>Left Lateral Gastrocnemius</td>
<td>8.43 ± 9.67</td>
<td>-3.37 ± 20.50</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The results above show no statistical differences but it is important to point out some interesting trends that were discovered. In the patellar tendon graft subjects, they showed fatigue in both the right vastus lateralis as well as the left lateral gastrocnemius. The subjects with the hamstring tendon graft showed fatigue in only the left biceps femoris and this could be explained as an expected result given that two of the three subjects had reconstructive surgery in their left leg, thus making left biceps femoris weaker during the rehabilitation period. The only muscle that could be potentially different between the groups was the vastus lateralis (p=0.20).

4.0 Discussion

The motivation for this study was based on a few different studies, that investigated the advantages and disadvantages of the different types of ACL injuries, specifically hamstring tendon graft and patellar tendon graft. Additionally, there were other studies that using the technology of motion capture, electromyography, and a force platform to evaluate ACL injuries. This study was modified to evaluate and compare the different surgical techniques over the course of time whereas some studies would be evaluating the patients well after surgery. This study specifically evaluated subjects that were still in the rehabilitation process within one year of their ACL surgery. The
comparison for the ACL-R group to the control group is important to determine what the baseline data should be like.

4.1 Kinematic Data

There are some interesting trends that were found when looking at the motion capture data from both groups of subjects. While the differences that were found appeared to be minor, a small part the study was to investigate whether or not the use of this technology would be beneficial to the rehabilitation progress. This was determined to be true. Based on the kinematic data, it was possible to see the progress over time for the subjects in the ACL-R group. Those with the ACL reconstructive surgery trended towards the mean value of the control group which ranged from four to five degrees over the course of the six trials in terms of the knee flexion data. This is important to take note of because the typical recovery time from this type of injury is approximately 9 months. Most of the subjects that had ACL surgery were 9 months to 12 months out of surgery at conclusion of the study. As expected, the subjects in the ACL-R group improved and regressed to the mean value of the control group. There was no statistical significance between the two groups, but with a larger study the average difference in knee flexion between the groups may become significant.

However, the main goal of the study was to prove whether or not the one type of ACL reconstructive surgery was more beneficial than the other. In fact, the kinematic motion capture data showed one type of surgery is favored over the other. Figures 18 and 19 show the difference in knee flexion between the two legs in each of the five subjects over the course of the 12 week study. While the differences were not statistically significant, there is still a noticeable contrast between the surgical techniques. By the end of the study, the subjects with the hamstring tendon graft showed improvement while the subjects with the patellar tendon graft had a more of a
variation where it hard to see whether or not the subjects improved. This suggests that the hamstring tendon graft may be a better approach for better knee flexion in the long run. This data could be interpreted in another way. While the six trials over a course of three months was sufficient for this study, it may be beneficial to evaluate the subjects from the beginning of their rehabilitation and study the full physical therapy process.

4.2 Force Platform Data

The force platform analysis was separated into two parts. The first one being the ground reaction forces to analyze to forces in the y-direction during the sit-to-stand exercise. The second was the moments in the z-direction to analyze to the sway in the mediolateral plane. The trends that we discovered in this data are quite interesting.

Beginning with the ground reaction forces in the y-direction, the results were used to compare those in the ACL-R group to the control group. In addition, the ACL-R group was compared between the hamstring and patellar tendon graft surgeries. When analyzing the graphs for the hamstring tendon subjects during the sit-to-stand activity, they follow a similar trend where they start at approximately 80% body weight in trial 1 and increase to approximately 100% body weight in trial 6. The explanation for this would be that, at the beginning of the study, the subjects may not have been putting their full weight on during this motion. It is possible that the participants did not feel comfortable putting full pressure on their surgically repaired knee. On the other, the subjects with the patellar tendon graft began slightly above 100% body weight at trial 1 and decreased towards 100%. These subjects were more variable than those with the hamstring tendon graft. It is possible that the subjects in this group started over 100% body weight as they were overcompensating for the injury. This could also mean that they were not sufficiently balanced.
when they were performing the sit-to-stand activity. However, when comparing the control and ACL-R subjects, there were no statistically significant differences that were found.

Second, when looking more into the moments in the z-direction, it is possible to analyze the movements of the in the mediolateral plane or their sway to the left or right side of their body. Again, the subjects with the hamstring tendon graft and patellar tendon graft follow similar trends within the groups. The subjects with the hamstring tendon graft all began at around 6% body weight, slightly increased by trial 2 and 4 to approximately 8% and then decreased by down to around 6% body weight. This shows that these subjects to have less variability in their sway from one side to the other during the normal sit-to-stand exercise. The subjects with the patellar tendon graft show an interesting trend where the percent body weight exponential decreases until trial 4 before leveling off in both subjects. It possible that in this case that subjects would abnormally favor one side over the other at the beginning of the study and slowly became more comfortable over the course of the study. One factor that could impact this would be the amount of time that they were out from surgery. Another aspect of the analysis for the moment in the z-direction is investigating the other two types of sit-to-stand activities in which the subjects have their feet placed one in front of the other. There was no significant difference found in the between the different surgical techniques. However, for three of the subjects, the moment in the z-direction had a higher percentage of body weight when they were pushing off their healthy leg. A higher percentage of body weight in the z-direction signifies more movement. The subjects that had more movement may have been caused by less stability with their injured leg further away from their body.
4.3 EMG Sensor Data

The EMG sensors data provided some interesting and expected results when comparing the differences between those with the hamstring tendon graft and patellar tendon graft. The importance of this data is that it analyzing the muscular performance of the subjects during the squats. The procedure that was used to analyze this data as far as determining the percent activation was used in the paper by Zeller et al. The EMG signals were collected during all of the activities in the study, the chair squat, sitting-to-standing, and treadmill activities.

The first interesting result came when analyzing the males and females within the control group when looking at the vastus lateralis for the chair squat activity. There was a not a significant difference, but still difference in muscle activation for these subjects. This could be explained for a few reasons. As mentioned earlier, it could be caused be amount of exercise each of the subjects gets. Also, this difference may have occurred due to the physiological differences between males and females. Females tend to have a higher activation and exhibited quadriceps dominance in most cases (Hale). The difference in muscle activation between both legs could possibly be explained by this. Given that males and females have different muscle activation profiles, one could expect this result to occur. However, in the ACL-R group it was determined that there was no significant difference between the male and female subjects. It is possible that due to their injuries that it cannot be seen as clearly like in the control group. Though when looking at the differences between the hamstring tendon and patellar tendon graft surgery, it was noticed that the subjects with the patellar tendon graft had a lower mean difference in activation between each leg than did those in the hamstring group. This could potentially explain some compensation that those in hamstring tendon group may have experienced. Ideally, the subjects should have minimal difference in activation between each leg and this was more so expressed in the patellar tendon subjects.
During the sit-to-stand activity, it was also determined that there were no significant differences between the groups or gender. Additionally, the subjects all showed a similar muscle activation. When analyzing the treadmill activity, the muscle activation between the legs was compared. The subjects in the ACL-R group showed strengthening in the left vastus lateralis as group during the 10 minute walking exercise. This is noteworthy because it shows that this muscle had a higher mean muscle activation difference than any of the others evaluated. It can be interpreted that since five out of the six subjects had the surgery in their left leg, one could expect this specific muscle to be more activated due to the surgical trauma.

When looking at the biceps femoris muscle, there were some interesting results as well. There was more variability in control group for this muscle during the chair squat activity and no statistically significant difference was seen between the male and female subjects. The subjects in the ACL-R group were more intriguing in this case. When comparing the surgical techniques, it was determined that there was not a statistically significant difference. However, there were some minor differences that could be explained by the type of surgery. The subjects with the hamstring tendon graft had a larger difference between left and right biceps femoris than those in the patellar tendon graft. This could be expected due to the nature of the surgery for the hamstring graft. Essentially, when the surgeons take the graft they inadvertently damage the hamstring muscle as a whole. It was clearly expressed by this data since the subjects had a greater difference. Similarly, when comparing the subjects in the ACL-R group during the sit-to-stand activity, there was not a significant difference in the biceps femoris muscle. Subjects in the patellar tendon group again had a smaller disparity when compared to that with the hamstring tendon graft. Again, this could be explained by the way surgery is performed and the weakening of the hamstring muscle as whole. Over time, it is possible that it would be fully functional, but during the rehabilitation process it
was not improved. This could potentially be discovered in a more long-term study. To further prove the idea that there was fatigue in the biceps femoris, the treadmill data could be looked at closer. The treadmill results showed that there was a significant difference in between the subjects in the control group and the ACL-R group. The control group showed strengthening of this muscle whereas the subject showed fatigue. When the subjects completed the walk on the treadmill, it safe to assume that a control subject would be “warmed up” thus causing this strengthening. However, those with ACL reconstructive surgery may have limited muscle activation over the walking period. A future addition could be having the subjects use the treadmill for an extended period of time to investigate greater fatigue.

The third muscle that was evaluated in this study was the lateral gastrocnemius, part of the calf muscle group. The subjects were analyzing between sexes in both the control group and ACL-R group. Additionally, the subjects in the ACL-R group were compared between the surgical techniques. There is a result for one of the subjects during the chair squat activity that should be discussed. Subject 1 with hamstring tendon reconstruction had a large difference in muscle activation over the course of the final three trials in the study (33.64%) between their two legs. Interestingly, the lateral gastrocnemius that had the lower overall percent activation was the opposite leg to the one in which the ACL was performed on. There are few reasons that come to mind and could potentially explain this outlier. The first one would be the potential noise in the signal that may have altered what was determined to be a peak or not by the C++ program. Additionally, a more interesting explanation for this anomaly would be there could be potential compensation or favoring of one leg over the other. It possible also that since the focus of the rehabilitation during regular physical therapy was on the injured leg that the healthy leg could have some muscle atrophy due to the inability to exercise on a regular basis. When looking among the
other subjects in the ACL-R group it appears that they had similar results. In this case, it is impossible to determine whether or not one surgical technique would be preferred over the other.

During the sit-to-stand activity, this muscle was also investigated. The subjects in the control group were divided by sex and it was determined that there was not a significant difference between the activation of the lateral gastrocnemius. This could be explained by the amount of exercise that the male subjects do compared to the female subjects. Additionally, when the male subjects exercise it is possible that they favor their dominant leg in many movements without even knowing it. The subjects in the ACL-R group had a large range of variability between the different surgical techniques making it difficult to make any determination about which technique would be preferred over the other.

The treadmill activity showed no significant differences between the control group and the ACL-R group. Interestingly, the subjects in ACL-R group showed fatigue in the left lateral gastrocnemius yet there was a large standard deviation between each of the subjects. Additionally, the subjects in the control group showed fatigue in both the left and right side. It is possible that the since they were walking for ten minutes, the calf fatigued more since it is believed to do most of the work during the natural gait pattern. When comparing those with the different surgical techniques, only the left lateral gastrocnemius showed fatigue. Since the two subjects in this group had surgery on their left leg it is possible their right leg would take over most of the muscle activation and compensate for the left side.

4.4 Limitations

During the study there were some important limitations that need to be discussed. First and foremost, the sample size of the study must be considered. The study size in this case was 23 subjects: 8 in the ACL-R group and 15 in the control group. While groups were split evenly...
between males and females and the different types of graft surgery in the ACL-R group, the sample size was too small to see any significant differences. A larger multicenter, controlled study should be done to investigate the minor anomalies that were seen in results from this study to better support the trends that were found in the data for this project.

The next limiting factor was the age range of the study. The subjects recruited for the study were only UConn students between the ages of 18 and 23 years of age. It is possible that more interesting results would be seen if this age range was extended to people around the age of 30 or 40 years. The third limitation would be a combination of the software and computer itself. The Motion Monitor software tended to freeze up or crash at times and would inhibit the data collection process. This would sometimes require the motion capture to be recalibrated or even a full computer shut down to fix the issue. This would not be the best case scenario especially when a subject was present for their data collection trial. In some cases the participants needed to come back at a later date to redo the trial. It is possible this issues like this happened for a few reasons. One being the computer itself. It was not specifically designed to handle this type of motion capture software thus causing the program to run slower than it typically should. A newer computer with more memory and hard drive space would allow for better overall performance.

4.5 Future Work

There were some interesting takeaways from this study that could be applied to future studies using this type of equipment. Based on the results of the study, it was possible analyze the physiological differences between the subjects in both the control as well as the ACL-R group. It would be intriguing to see this study continued with new participants who have just begun physical therapy. By doing this, it would be possible to interpret the changes from the beginning to when the people were back to full strength. When conducting this further, it would also be interesting to
evaluate the participants at the different stages of the rehabilitation process in which would require additional or slightly modified exercises. This could potentially be used to evaluate different milestones and landmarks during the therapy process. Investigating this, could open up new techniques to monitor progress during rehabilitation. In addition, it would be necessary to investigate the timing and speed of which the exercises are performed. This would be of interest in determining whether someone with an ACL injury could perform the same tasks as someone in the control group at the same pace or not, thus determining when they would be fully recovered from their injury. This could also show whether the muscle was firing at similar times when doing bilateral activities.

Another aspect of future work on this topic of ACL reconstructive surgeries would be to evaluate the subjects in a randomized study. For example, the subjects with the ACL injuries would be divided into two groups, one receiving the real-time feedback as was done in this study and the other group having regular physical therapy without the implementation of the motion capture, EMG, or force platform technology. This type of study would clear up whether or not the process of real-time feedback could be used to further improve the recovery time from the typical nine to twelve months.

Lastly, this experimental setup was specifically designed for the activities in the study. If the study would be extended to different exercises future researchers should consider a camera setup that could better suit their needs. A semi-circle, as used in this study, would not be helpful if someone was interested in tracking the compensation for the hip. More cameras and markers would be required to evaluate the subjects from the back, where the hip markers would be placed. If this is a possibility, it would greatly improve the motion capture and kinematic data determined from each subject.
5.0 Conclusion

The study some interesting results that should definitely further investigated for patients in the recovery phase from an isolated ACL tear. As mentioned, the subjects were compared within the control group as well as in the ACL-Reconstruction (ACL-R) group. Within the control group, the subjects were compared between males and females. In the ACL-R group, the subjects were compared between both males and females and the type of surgery. When considering the knee flexion data the hamstring graft is more beneficial than the patellar tendon graft in terms of showing progress over the course of the study. The subjects with the hamstring tendon graft showed that they had less of a difference in knee flexion as was hypothesized. This is one aspect of the data that would be interesting to further investigate with a larger patient group. With regards to EMG and force platform results, the data proved either inconclusive or favoring the patellar tendon graft technique during the chair squat and sit to stand activities. More specifically, the EMG results for the biceps femoris showed that the subjects with the hamstring tendon graft had a greater difference between their two legs. This was expected as the hamstring group would have less muscle function because of the type of surgery that they had performed on them.

ACL injuries have become a commonplace in sports thus making it imperative to develop effective physical therapy techniques that enable athletes to regain the strength necessary to compete. With this research, it is possible to conclude that real-time feedback may be a useful approach for ACL rehabilitation, and in determining which surgical approach may be most ideal for recovering patients.
6.0 References


Massachusetts General Hospital, "Exercises after injury to the Anterior Cruciate Ligament (ACL) of the Knee," 2015.


Acknowledgements

I would like to take this time to thank all of the people involved in the study and throughout the thesis process. First, I would like to acknowledge my mentor and major faculty adviser Dr. Krystyna Gielo-Perczak for all of her help and guidance throughout my two years as a graduate student. I would also like to thank my thesis committee of Dr. Sangamesh Kumbar and Dr. Patrick Kumavor. Next, I wish to my wonderful group of graduate and undergraduate students for all of their help with data collection and analysis: Anna Roto, Malavika Suresh, Shaniel Bowen, Morgan DaSilva, Allie Hill, Alexa Kiernan, Brittany Morgan, Alexander Tkeshelashvili, and Emily Wycallis. Without this group, the study would not have gone as smoothly as it did. I would also like to thank Dr. David Kaputa, Jonathan Scannell, and Nathan Sattar for their computer programming prowess during the data processing phase. I would like thank Dr. Lindsay Lepley and Dr. Lindsey DiStefano for their help and assistance during the IRB process as well as the EMG positioning. Additionally, I would like to acknowledge John Chomack, Nicholas Lombardi, Ryan Schafer, and Lindsay Yanaros for their previous research with the equipment. Finally, I would like to acknowledge all of the study participants for their dedication to the study all semester long. Without their time and effort none of this would have been possible. Overall, I wish to thank the Biomedical Engineering Department at UConn as a whole for their support during this research and providing the necessary equipment to complete the project.

Appendix A - EMG Average Calculations C++ Code

/**
 * BME Peak Calculator
 * by Jonathan Scannell
 * jonathan.scannell@engineer.uconn.edu
 */

#include <algorithm>
#include <cstdlib>
#include <fstream>
#include <iostream>
#include <string>
#include <vector>
using namespace std;

struct frame
{
    int number;
    double rightQuad;
    double leftQuad;
    double rightHamstring;
    double leftHamstring;
    double rightCalf;
    double leftCalf;
    double peakRightQuad;
    double peakLeftQuad;
    double peakRightHamstring;
    double peakLeftHamstring;
    double peakRightCalf;
    double peakLeftCalf;
};

// Input Data
vector<frame> data;

// Output Data
double rightQuadMax = 0, rightQuadPeakAvg;
double leftQuadMax = 0, leftQuadPeakAvg;
double rightHamstringMax = 0, rightHamstringPeakAvg;
double leftHamstringMax = 0, leftHamstringPeakAvg;
double rightCalfMax = 0, rightCalfPeakAvg;
double leftCalfMax = 0, leftCalfPeakAvg;

//Prototypes
void input(char*);
void algorithm();
void readHeader(fstream*);
void outputCSV(char*, char*);
bool compare(double, double);

// Other Data
int expectedPeaks;
int main(int argc, char* argv[]) {
    cout << "Working on file [" << argv[1] << "]..." ;
    expectedPeaks = atoi(argv[4]);
    if (expectedPeaks < 1) {
        cout << "Failure...invalid argument expectedPeaks=[" << expectedPeaks << "]" << endl;
        return 1;
    }
    input(argv[1]);
    algorithm();
    outputCSV(argv[2], argv[3]);
    cout << "done!" << endl;
    return 0;
}

void input(char* inputFile) {
    fstream fin;
    fin.open(inputFile, fstream::in);

    // skip to the good stuff
    readHeader(&fin);

    frame f;
    while (fin >> f.number >> f.rightQuad >> f.leftQuad >> f.rightHamstring >> f.leftHamstring >> f.rightCalf >> f.leftCalf >> f.peakRightQuad >> f.peakLeftQuad >> f.peakRightHamstring >> f.peakLeftHamstring >> f.peakRightCalf >> f.peakLeftCalf) {
        data.push_back(f);
    }

    fin.close();
}
/**
* skips over the header text
* so we can get to the raw data
*/
void readHeader(fstream* fin)
{
    string line;
    while (getline(*fin, line))
    {
        if (line.empty())
        {
            break;
        }
    }
    getline(*fin, line);
}

void algorithm()
{
    // Step 1: Calculate Max Peak
    double rightQuadSum = 0;
    double leftQuadSum = 0;
    double rightHamstringSum = 0;
    double leftHamstringSum = 0;
    double rightCalfSum = 0;
    double leftCalfSum = 0;
    for (unsigned i = 0; i < data.size(); i++)
    {
        rightQuadMax = max(rightQuadMax, data[i].peakRightQuad);
        rightQuadSum += data[i].peakRightQuad;

        leftQuadMax = max(leftQuadMax, data[i].peakLeftQuad);
        leftQuadSum += data[i].peakLeftQuad;

        rightHamstringMax = max(rightHamstringMax, data[i].peakRightHamstring);
        rightHamstringSum += data[i].peakRightHamstring;

        leftHamstringMax = max(leftHamstringMax, data[i].peakLeftHamstring);
        leftHamstringSum += data[i].peakLeftHamstring;

        rightCalfMax = max(rightCalfMax, data[i].peakRightCalf);
        rightCalfSum += data[i].peakRightCalf;

        leftCalfMax = max(leftCalfMax, data[i].peakLeftCalf);
        leftCalfSum += data[i].peakLeftCalf;
    }
double rightQuadAvg = rightQuadSum / data.size();
double leftQuadAvg = leftQuadSum / data.size();
double rightHamstringAvg = rightHamstringSum / data.size();
double leftHamstringAvg = leftHamstringSum / data.size();
double rightCalfAvg = rightCalfSum / data.size();
double leftCalfAvg = leftCalfSum / data.size();

// Step 2: Find Peaks
double rightQuadLocal = 0;
double leftQuadLocal = 0;
double rightHamstringLocal = 0;
double leftHamstringLocal = 0;
double rightCalfLocal = 0;
double leftCalfLocal = 0;
vector<double> rightQuadPeaks;
vector<double> leftQuadPeaks;
vector<double> rightHamstringPeaks;
vector<double> leftHamstringPeaks;
vector<double> rightCalfPeaks;
vector<double> leftCalfPeaks;
for (unsigned i = 0; i < data.size(); i++)
{
    // Right Quad
    if (rightQuadLocal > rightQuadAvg && data[i].peakRightQuad < rightQuadAvg)
    {
        rightQuadPeaks.push_back(rightQuadLocal);
        rightQuadLocal = 0;
    }
    else
    {
        rightQuadLocal = max(rightQuadLocal, data[i].peakRightQuad);
    }

    // Left Quad
    if (leftQuadLocal > leftQuadAvg && data[i].peakLeftQuad < leftQuadAvg)
    {
        leftQuadPeaks.push_back(leftQuadLocal);
        leftQuadLocal = 0;
    }
    else
    {
        leftQuadLocal = max(leftQuadLocal, data[i].peakLeftQuad);
    }

    // Right Hamstring
if (rightHamstringLocal > rightHamstringAvg && data[i].peakRightHamstring < rightHamstringAvg)
{
    rightHamstringPeaks.push_back(rightHamstringLocal);
    rightHamstringLocal = 0;
}
else
{
    rightHamstringLocal = max(rightHamstringLocal, data[i].peakRightHamstring);
}

// Left Hamstring
if (leftHamstringLocal > leftHamstringAvg && data[i].peakLeftHamstring < leftHamstringAvg)
{
    leftHamstringPeaks.push_back(leftHamstringLocal);
    leftHamstringLocal = 0;
}
else
{
    leftHamstringLocal = max(leftHamstringLocal, data[i].peakLeftHamstring);
}

// Right Calf
if (rightCalfLocal > rightCalfAvg && data[i].peakRightCalf < rightCalfAvg)
{
    rightCalfPeaks.push_back(rightCalfLocal);
    rightCalfLocal = 0;
}
else
{
    rightCalfLocal = max(rightCalfLocal, data[i].peakRightCalf);
}

// Left Calf
if (leftCalfLocal > leftCalfAvg && data[i].peakLeftCalf < leftCalfAvg)
{
    leftCalfPeaks.push_back(leftCalfLocal);
    leftCalfLocal = 0;
}
else
{
    leftCalfLocal = max(leftCalfLocal, data[i].peakLeftCalf);
}
// Step 3: Calculate Average Peak
int count;

// Right Quad
sort(rightQuadPeaks.begin(), rightQuadPeaks.end(), compare);
double rightQuadPeakSum = 0;
count = 0;
for (unsigned i = 0; i < expectedPeaks && i < rightQuadPeaks.size(); i++)
{
    rightQuadPeakSum += rightQuadPeaks[i];
count++;
}
rightQuadPeakAvg = rightQuadPeakSum / count;

// Left Quad
sort(leftQuadPeaks.begin(), leftQuadPeaks.end(), compare);
double leftQuadPeakSum = 0;
count = 0;
for (unsigned i = 0; i < expectedPeaks && i < leftQuadPeaks.size(); i++)
{
    leftQuadPeakSum += leftQuadPeaks[i];
count++;
}
leftQuadPeakAvg = leftQuadPeakSum / count;

// Right Hamstring
sort(rightHamstringPeaks.begin(), rightHamstringPeaks.end(), compare);
double rightHamstringPeakSum = 0;
count = 0;
for (unsigned i = 0; i < expectedPeaks && i < rightHamstringPeaks.size(); i++)
{
    rightHamstringPeakSum += rightHamstringPeaks[i];
count++;
}
rightHamstringPeakAvg = rightHamstringPeakSum / count;

// Left Hamstring
sort(leftHamstringPeaks.begin(), leftHamstringPeaks.end(), compare);
double leftHamstringPeakSum = 0;
count = 0;
for (unsigned i = 0; i < expectedPeaks && i < leftHamstringPeaks.size(); i++)
{
    leftHamstringPeakSum += leftHamstringPeaks[i];
count++;
}
leftHamstringPeakAvg = leftHamstringPeakSum / count;

// Right Calf
sort(rightCalfPeaks.begin(), rightCalfPeaks.end(), compare);
double rightCalfPeakSum = 0;
count = 0;
for (unsigned i = 0; i < expectedPeaks && i < rightCalfPeaks.size(); i++)
{
    rightCalfPeakSum += rightCalfPeaks[i];
count++;
}
rightCalfPeakAvg = rightCalfPeakSum / count;

// Left Calf
sort(leftCalfPeaks.begin(), leftCalfPeaks.end(), compare);
double leftCalfPeakSum = 0;
count = 0;
for (unsigned i = 0; i < expectedPeaks && i < leftCalfPeaks.size(); i++)
{
    leftCalfPeakSum += leftCalfPeaks[i];
count++;
}
leftCalfPeakAvg = leftCalfPeakSum / count;

// fileName is the file that is currently being processed
void outputCSV(char* outputFile, char* fileName)
{
ofstream fout;
fout.open(outputFile, ios_base::app);

fout << fileName << "",
    << rightQuadMax << ",",
    << rightQuadPeakAvg << ",",
    << leftQuadMax << ",",
    << leftQuadPeakAvg << ",",
    << rightHamstringMax << ",",
    << rightHamstringPeakAvg << ",",
    << leftHamstringMax << ",",
    << leftHamstringPeakAvg << ",",
    << rightCalfMax << ",",
    << rightCalfPeakAvg << ",",
    << leftCalfMax << ",",
    << leftCalfPeakAvg << endl;
fout.close();
// Compare for sorting
bool compare(double i, double j)
{
    return (i>j);
}