

ORIGINAL PAPER

BIOMECHANICAL ANALYSIS OF DIFFERENT ANTERIOR CRUCIATE LIGAMENT SURGICAL TECHNIQUES AND THEIR INFLUENCE ON REHABILITATION

ANALIZA BIOMECHANICZNA RÓŻNYCH TECHNIK CHIRURGICZNYCH REKONSTRUKCJI WIĘZADŁA KRZYŻOWEGO PRZEDNIEGO I ICH WPŁYWU NA REHABILITACJĘ

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ABSTRACT

Anterior cruciate ligament (ACL) tears are one of the most prevalent activity-related injuries among athletes in the United States. ACL reconstructive surgeries are typically done using a patellar tendon graft or hamstring tendon graft. There is 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. 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.

The results of this pilot study demonstrate that the surgical techniques can be evaluated using a dynamic multi-system approach. These systems include 1) a motion capture system, 2) electromyography (EMG) sensors, and 3) a force platform system. The significant parameters included knee flexion, maximum muscle activity from the muscles around the knee, and balance control variables.

The results of the study revealed that 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. 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.

Keywords: ACL, patellar, hamstring, graft, rehabilitation

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STRESZCZENIE

Zerwania przedniego więzadła krzyżowego (ACL) są jednym z najbardziej rozpowszechnionych urazów związanych z aktywnością wśród sportowców w Stanach Zjednoczonych. Operacje rekonstrukcyjne ACL są zwykle wykonywane przy użyciu przeszczepu ścięgna rzepki lub ścięgna udowego. Prowadzona jest dyskusja, który rodzaj operacji przeszczepu jest najlepszy, ponieważ preferencje chirurga między tymi dwoma różnią się. Głównym celem przedstawionego badania było porównanie wyżej wymienionych technik chirurgicznych ACL. Drugim celem było dostarczenie fizjoterapeutom i pacjentom informacji zwrotnej w czasie rzeczywistym postępów rehabilitacji w odzyskiwaniu sprawności fizycznej w miarę upływu czasu podczas wykonywania proponowanego schematu ćwiczeń fizycznych.

Wyniki tego badania pilotażowego pokazują, że techniki chirurgiczne można oceniać za pomocą dynamicznego podejścia wielosystemowego. Systemy te obejmują 1) system analizy ruchu, 2) system aktywności mięśni (EMG) i 3) system równowagi ciała. Istotne parametry obejmowały mierzenie zgięcia kolana, maksymalną aktywność mięśni wokół kolana oraz zmienne (siły i momenty) sterujące równowagą ciała.

Wyniki badania wykazały, że biorąc pod uwagę dane dotyczące zgięcia kolana, przeszczep ścięgna udowego jest bardziej korzystny niż przeszczep ścięgna rzepki pod względem wykazywania postępu w rehabilitacji. Biorąc pod uwagę aktywność mięśni (EMG) i pomiary równowagi ciała wyniki okazały się niejednoznaczne lub faworyzowały technikę przeszczepu ścięgna rzepki podczas przysiadu na krześle i wstawania z krzesła. Dzięki tym badaniom możemy stwierdzić, że sprzężenie zwrotne w czasie rzeczywistym może być użytecznym podejściem do rehabilitacji ACL i określenia, które podejście chirurgiczne może być najbardziej idealne w rehabilitacji pacjentów.

Słowa kluczowe: przednie więzadło krzyżowe, ścięgno udowe, przeszczep, rehabilitacja

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, 2015). Currently, it takes up to nine months for an athlete or non-athlete to fully recover from this type of injury. In such cases, the additional complication of a meniscus tear can extend time of rehabilitation to one year (Huber *et al.*, 2013). For some, this may be too long, especially those whose livelihood depends on his or her ability to participate in physical activity. This type of injury is common in both young adults and individuals over the age of forty (Mall *et al.*, 2014). Given these facts, it is important to study the current physical therapy approach and patient outcomes (Suresh *et al.*, 2018). The current gold standard of rehabilitation from ACL injuries is based mainly on visual cues and suggestions from the physical therapists, however this has some disadvantages. It is important to improve on these processes with 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 different 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.

The study focuses mainly on those with ACL injuries currently in the rehabilitation process or those still doing at-home exercises. The reason for this study is to evaluate the different surgical techniques and determine which, if any, is more beneficial than the other. 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 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.

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 two different surgical techniques, the patellar tendon graft and the hamstring tendon graft. 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. The data collection will be done using three different systems: an Optitrack Motion Capture System along with Motion Monitor, Delsys Trigno Wireless Electromyography (EMG) Sensors, and an AMTI AccuSway Force Platform.

Aim

The goal of this experiment is 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, while simultaneously comparing the knee flexion between an individual in the control group and someone that has injured their ACL during completion of the specified and requested physical therapy exercises. A secondary goal is 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 therapists to monitor the progress of their patients over time.

Material and methods

A total of twenty-three subjects were used in this pilot study: fifteen in the control group and

eight with ACL reconstructive surgery within one since surgery. All study participants were between the ages of 18 and 23 when the study began, and the study included both male and female participants. Subjects in the control group were included in the study if they were active and had no previous knee injuries or conditions. Female subjects averaged 150 lbs (\pm 30 lbs) and were an average of 63 in (\pm 6 in) according to the CDC averages (Fryar, 2012). Male subjects were an average 172.5 lbs (\pm 37.5 lbs) and an average of 68.5 in (\pm 6.5 in) according to CDC averages. Participants were removed from the study if they failed to attend two scheduled appointments without notice.

Prior to beginning the study, the participants came to the lab after expressing interest 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 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.
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 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 and saved.

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 been 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.

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 are detected by infrared light sent out by the cameras, allowing the movements of the patient to be tracked. For the purposes of this study, the six cameras were aligned in a semi-circle manner around the subject standing on either the treadmill or the force platform. The cameras are thirty degrees apart in groups of three. The reason for this type of setup is to ensure the entire subject area is captured. Each camera runs at 120 frames per

second and has a horizontal field of view of 56° in the stock lens and a horizontal field of view of 42° in the optional lens. Motion capture data was filtered using a Butterworth filter of 20Hz.

As can be seen in Figure 1 below, the subject is standing on the AMTI Accusway Platform ready to perform either the chair squat or the sitting to standing activity. 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.

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. These were the muscles that were evaluated over the course of the study.

Filters were used to extract any type of noise that is coming from the electric wiring in the device itself. A 60 Hz notch filter was used in this case. In addition to the notch filter, it is significant to place a bandpass filter on the signal from the EMG sensors. The high pass filter chosen for each muscle in the study was 20 Hz and the low pass filter of 350 Hz to create the bandpass filter. 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 as 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 *et al.* 2003). The following equation represents how this will be determined:

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

Using equation (1) above, it is possible to determine whether someone with an ACL injury has a muscle that is not being 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

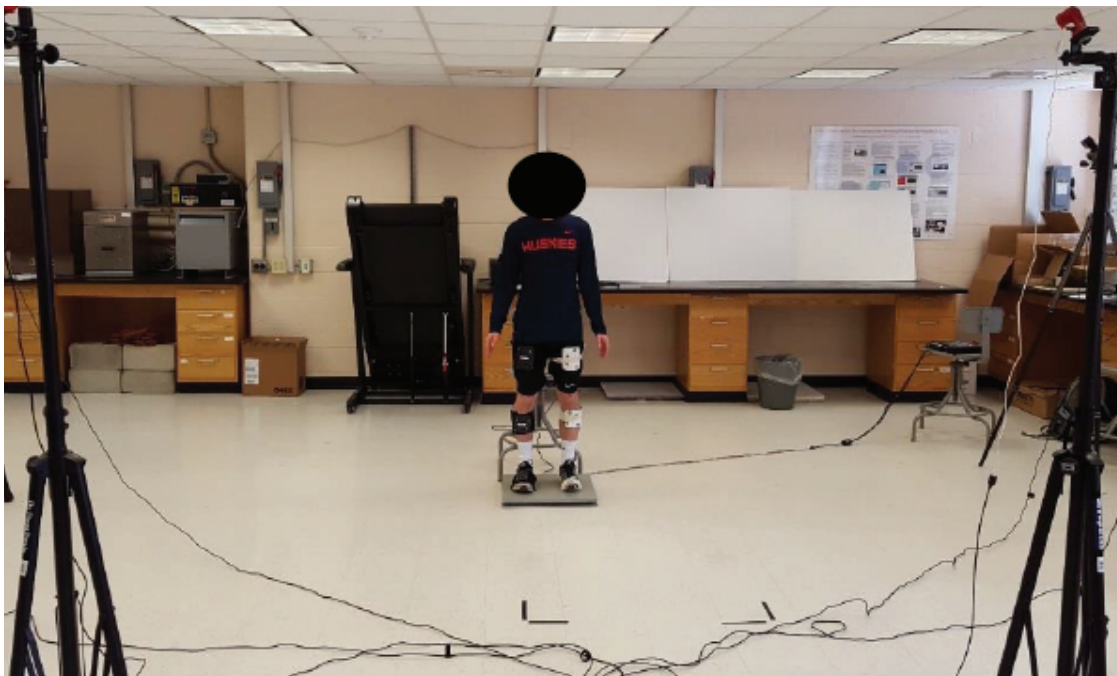


Figure 1. Experimental Setup with Force Platform.

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.

Force Platform Analysis

From the force platform, there are a few important measurable 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. When the subjects in the study were asked to perform a series of three sitting to standing exercises (feet shoulder width apart, left foot in front of the right foot, right foot in front of the left foot), the maximum force in the y direction (F_ymax), or ground reaction force, was calculated in order to interpret how much of their body weight the subjects were exerting on the force platform during a given movement, during a given trial. The equation for this is listed below:

$$\%Body\ Weight = \frac{Ground\ Reaction\ Force\ Y\ Direction\ (N)}{Body\ Weight\ of\ Subject\ (N)} * 100 \quad (2)$$

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:

$$\%Body\ Weight = \frac{Moment\ z\ (Nm)}{Body\ Weight * Height\ (Nm)} * 100 \quad (3)$$

Force platform data was filtered using a Butterworth filter of 20 Hz.

All data was collected and processed in The Motion Monitor (Innovative Sports Training, Inc., Chicago, IL).

Results and discussion

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.

As can be seen in Table 1, there was not a significant difference before and after the study. This shows that psychologically the participants felt that they only slightly improved after completing their respective physical therapy regimens.

Motion Capture Data

There are a variety of ways to analyze the kinematic data, one of which 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: the control group vs. the ACL-R group. This variable is significant due to the fact that those in 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.

For this analysis, the average maximum angle of knee flexion was found for 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 was the chair squat. From Figure 2 below, 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 was a high variability in the results as can be seen in the Table 2 below.

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. This can be seen in Table 3 below.

Table 1. Tegner and Lysholm Scoring.

	Tegner Before Injury (Out of 10)	Tegner After Injury (Out of 10)	Lysholm (out of 100)
Before Study	9.1	6.4	79.0
After Study	8.6	6.7	83.1

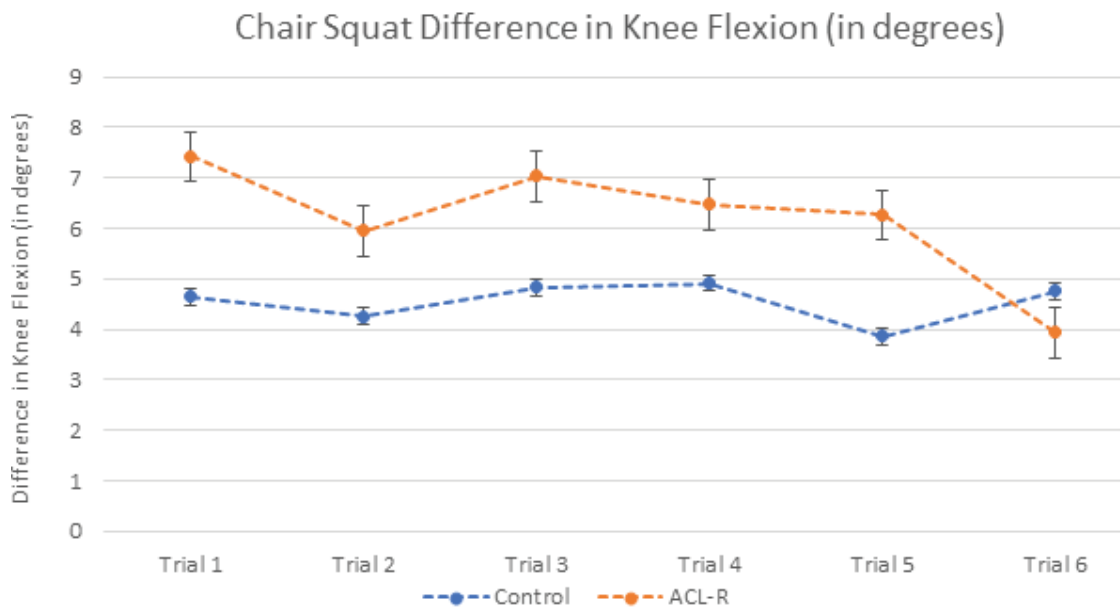


Figure 2: Difference in Chair Squat Knee Flexion.

Table 2. Difference in Knee Flexion (ACL-R Group).

Trial Number	Range (in degrees)	Average ± Standard Deviation (in degrees)
1	11.99	7.42 ± 4.21
2	13.44	5.95 ± 4.47
3	10.46	7.03 ± 3.67
4	11.30	6.46 ± 4.55
5	12.46	6.26 ± 4.69
6	9.02	3.93 ± 3.18

While there is a large variability it is still possible to see 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 goal was successful.

In addition, in a comparison between the two groups, it was important to compare the differences, if any, between those in the ACL-R group with different types of surgery as this was

Table 3. Comparison of Between Control and ACL-R Group Knee Flexion (*significance at p = 0.05).

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

the primary goal of the study. The knee flexion degree average difference was calculated in the same way as above by subject. While there were eight subjects in the ACL-R group, only five completed the full protocol. These results are displayed in the Figures 3–4 below.

was almost no difference between either leg. In addition, the patellar tendon subjects showed more of a variation in knee flexion during the chair squatting activity.

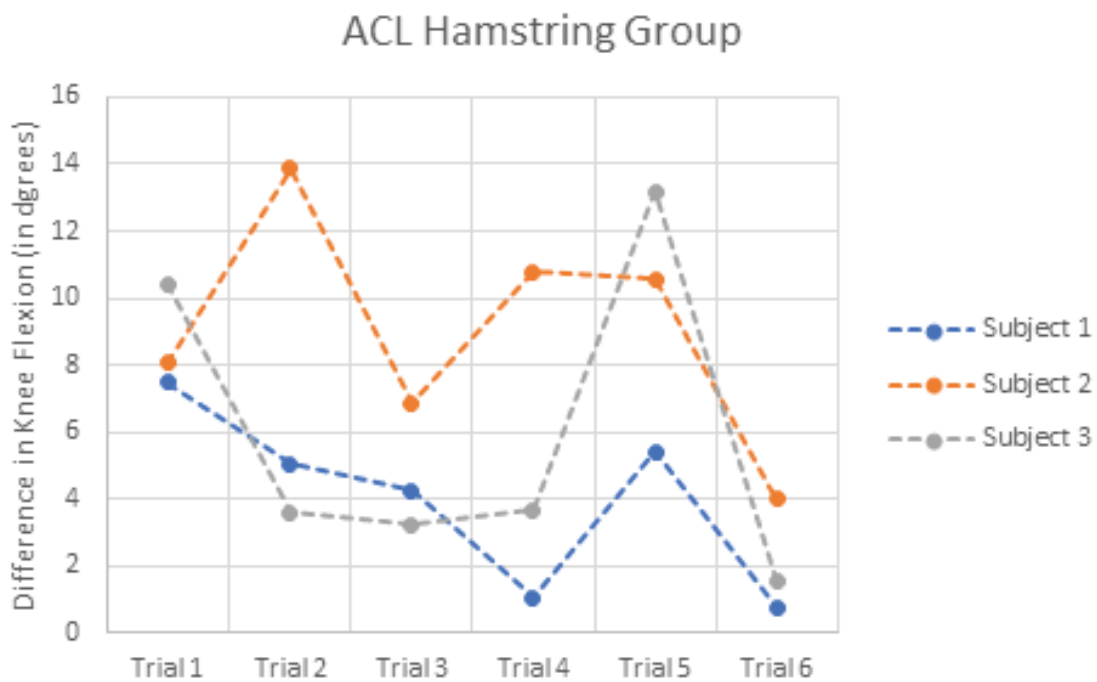


Figure 3. Hamstring Tendon Group Change in Knee Flexion vs. Time.

From the data in Tables 3–5, and Figures 3–4, 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. 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

Force Platform Data

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 whether those in the ACL group are putting more force on their uninjured knee.

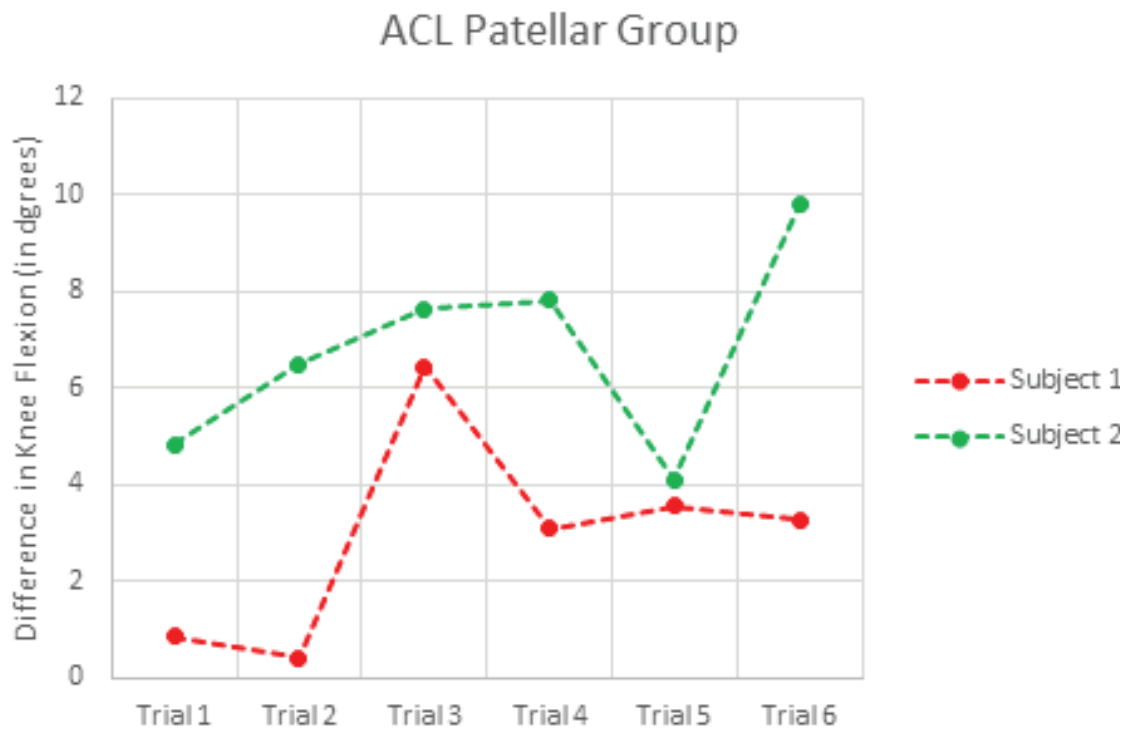


Figure 4. Patellar Tendon Group Change in Knee Flexion vs. Time.

Table 4. Comparison of ACL Groups Difference in Knee Flexion.

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

Table 5. Control Group Difference in Knee Flexion.

Units	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
	degrees	degrees	degrees	degrees	degrees	degrees
Maximum	13.13	16.15	11.74	10.46	8.64	10.19
Minimum	0.28	0.38	1.47	0.90	1.09	0.54
Range	12.84	15.77	10.28	9.56	7.54	9.65

The percent body weight used during the sitting to standing exercises was calculated here.

each of the six trials and only trial five ($p = 0.04$) proved to be statistically different between the

Table 6. Normal Sit-to-Stand in percent body weight (ACL-R Group).

Trial Number	Range (in %)	Average \pm Standard Deviation (in %)
1	45.61	97.34 \pm 19.06
2	46.48	111.41 \pm 17.43
3	46.27	102.05 \pm 15.14
4	27.77	110.19 \pm 11.07
5	42.77	102.04 \pm 16.57
6	30.87	96.88 \pm 11.36

As can be seen in Table 6, the results are variable in the ACL-R group when determining the percent body weight that is used in the particular exercise. As was the case with the kinematic data, it is important to compare those with the different types of ACL injuries.

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.

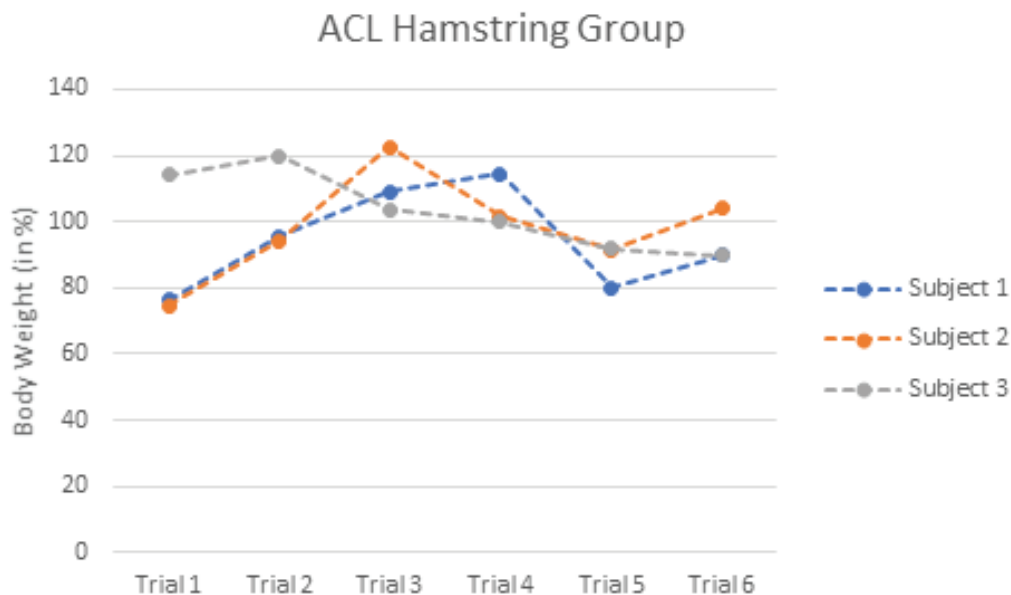


Figure 5. Ground Reaction Force progress over time (ACL Hamstring Tendon Graft).

From Figures 5 and 6 below 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

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). When investigating the subjects in with the different surgical techniques, the following results were discovered.

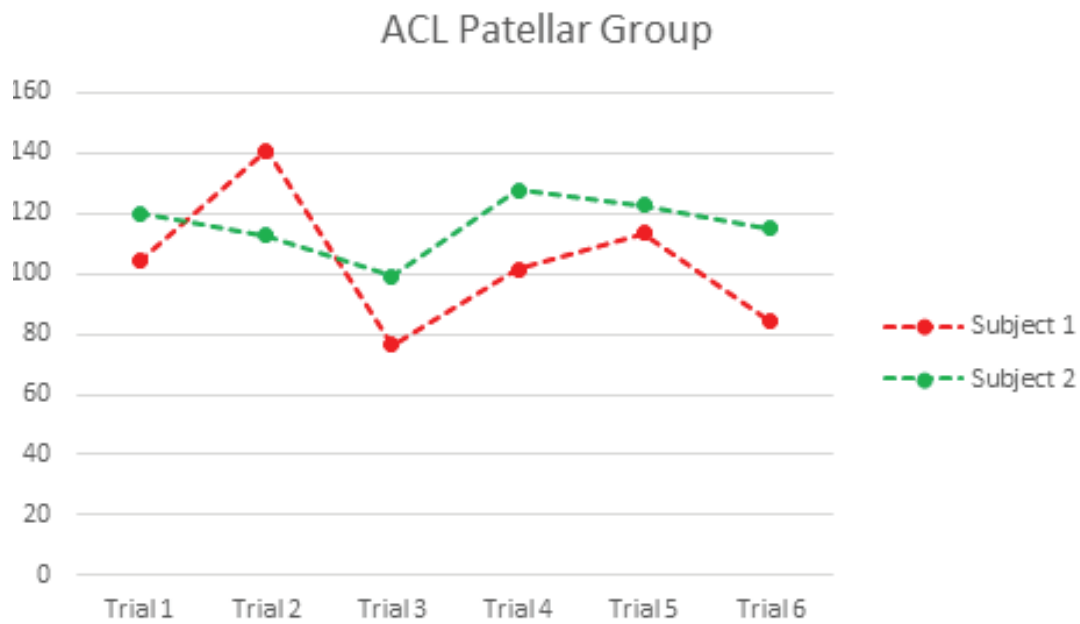


Figure 6. Ground Reaction Force Progress over Time (ACL Patellar Tendon Graft).

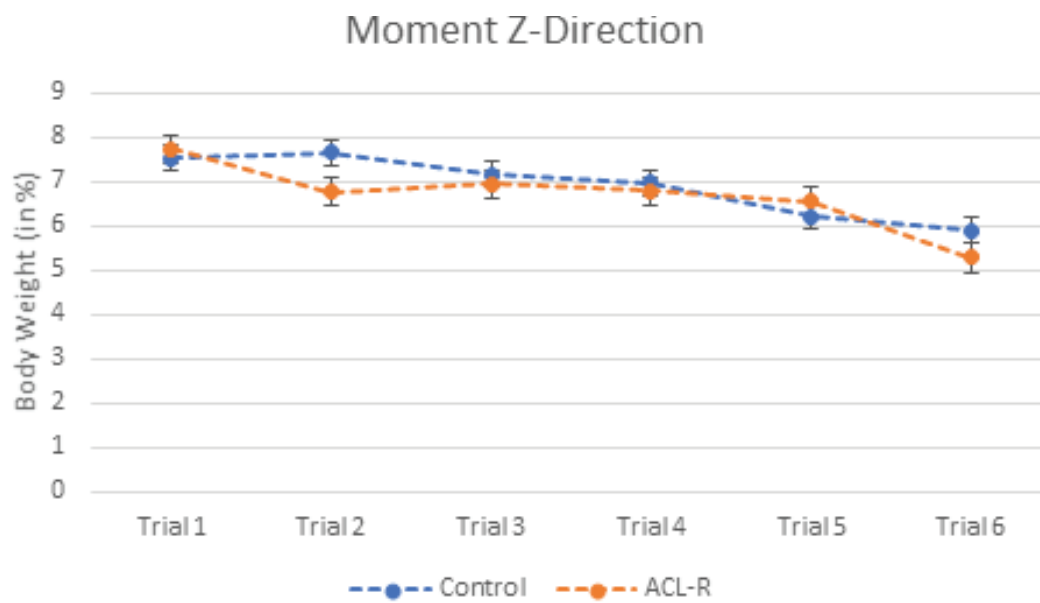


Figure 7. Moment Z-Direction for Normal Sit-to-Stand Activity.

Figure 7 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 ($p = 0.78$), as can be seen in Table 7. It is more interesting to look closer at the ACL-R group and compare the surgical techniques, as seen in Figures 8 and 9 below.

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 ($p = 0.95$). The trends that each of the subject groups follow is quite different however. In addition to evaluating the normal sit-to-stand technique, the subjects were asked to place both of their

Table 7. Ground Reaction Forces (Control vs. ACL-R) (*significance at p = 0.05).

Trial Number	Control Group	ACL-R Group	p-value*
	In %	In %	
1	104.44 ± 16.03	97.34 ± 19.06	0.45
2	109.16 ± 20.90	111.41 ± 17.43	0.86
3	104.07 ± 16.67	102.05 ± 15.14	0.79
4	113.50 ± 21.28	110.19 ± 11.07	0.64
5	101.29 ± 10.24	102.04 ± 16.57	0.92
6	98.75 ± 12.93	96.88 ± 11.36	0.75

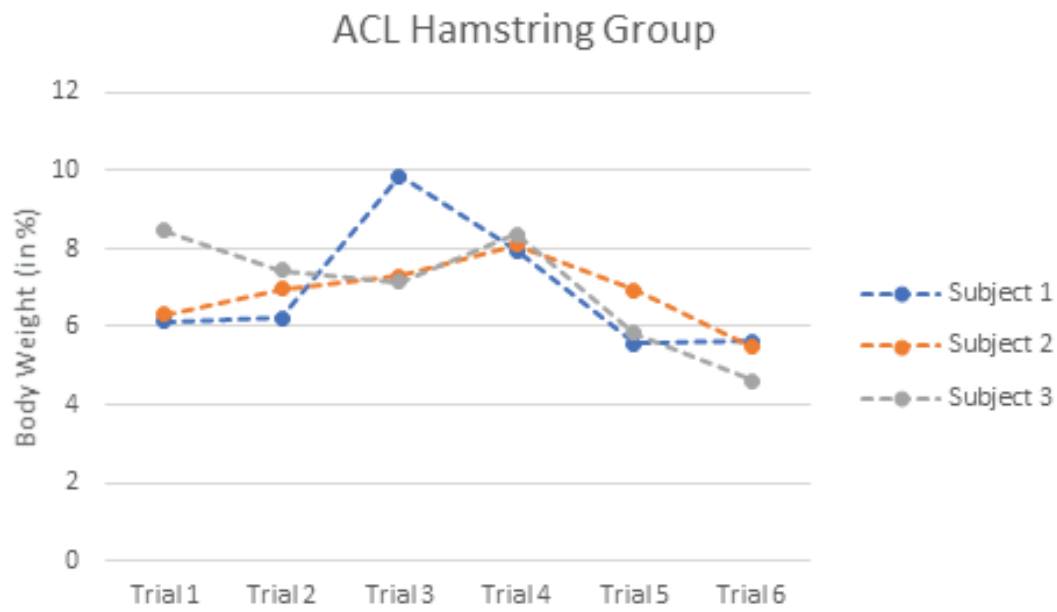


Figure 8. ACL Hamstring Graft Moment Z-Direction.

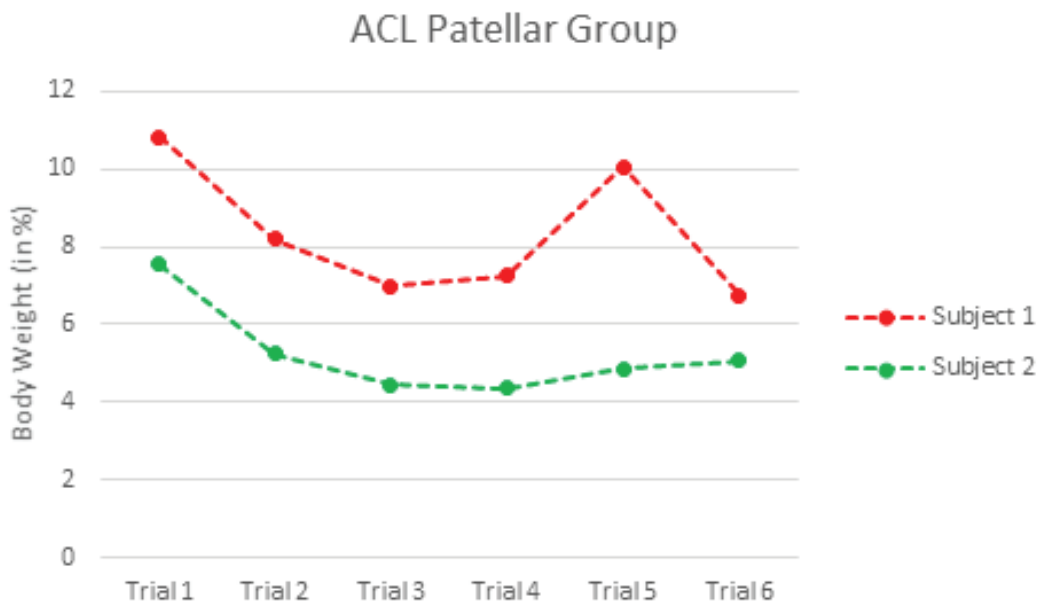


Figure 9. ACL Patellar Graft Moment Z-Direction.

feet in a line heel to toe first with the left foot in front and second with the right foot in front. The subjects in the ACL-R with the different surgical techniques were evaluated to investigate their movement in the in the mediolateral plane with push off leg being both the healthy leg and the injured leg. The differences are described in Table 8 below.

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.

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,

Table 8. Evaluation of movement in the mediolateral plane with push off leg being both the healthy leg and the injured leg.

Units	Push off Injured Leg	Push off Healthy Leg	Difference
	percent	Percent	percent
Hamstring			
Subject 1	8.03 ± 1.08	8.82 ± 1.99	0.79
Subject 2	7.44 ± 1.41	7.43 ± 1.73	-0.02
Subject 3	5.11 ± 0.64	6.04 ± 1.70	0.93
Patellar			
Subject 1	9.34 ± 1.99	9.08 ± 1.96	-0.26
Subject 2	5.63 ± 2.39	6.69 ± 1.71	1.06

The subjects in the ACL-R group (Table 8) 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.

EMG Analysis

Data from the EMG sensors were collected during all of the activities in the study. Data was taken from the final three trials for each of the 21 participants that were analyzed, as these were 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. Peaks were able to be chosen specifically and averaged using custom C++ and LabVIEW programs.

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 this data muscle by muscle to look at any potential differences between the control group and those with the different surgical techniques in the

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). These results can be seen in Figures 10–11.

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. 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

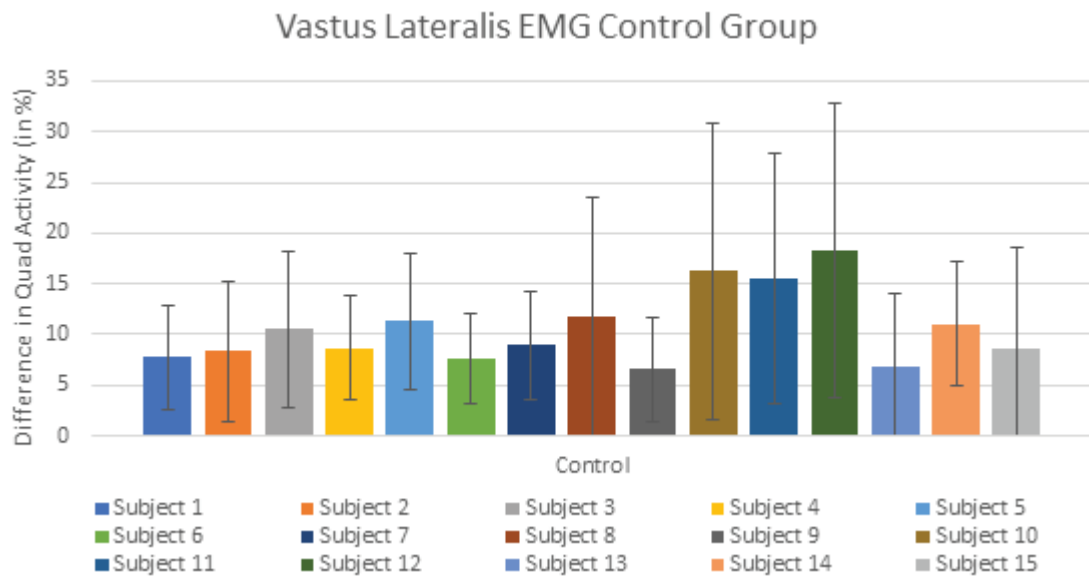


Figure 10. Vastus Lateralis Activation during Chair Squat (Control Group).

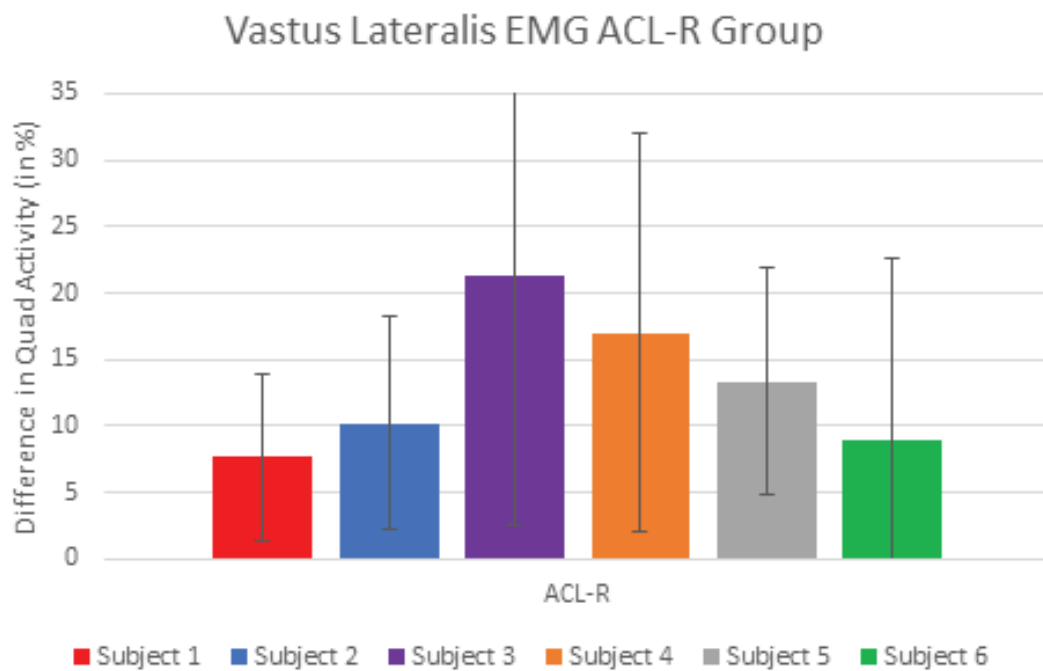


Figure 11. Vastus Lateralis Activation during Chair Squat (ACL Group).

the males and females within the control group. It was proven that there was no significance in this case ($p = 0.56$). This can be seen in Figures 12–13.

The next comparison that was drawn was the difference in hamstring activation 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 ($p = 0.55$).

The last muscle that was tested was the lateral gastrocnemius during the chair squat activity.

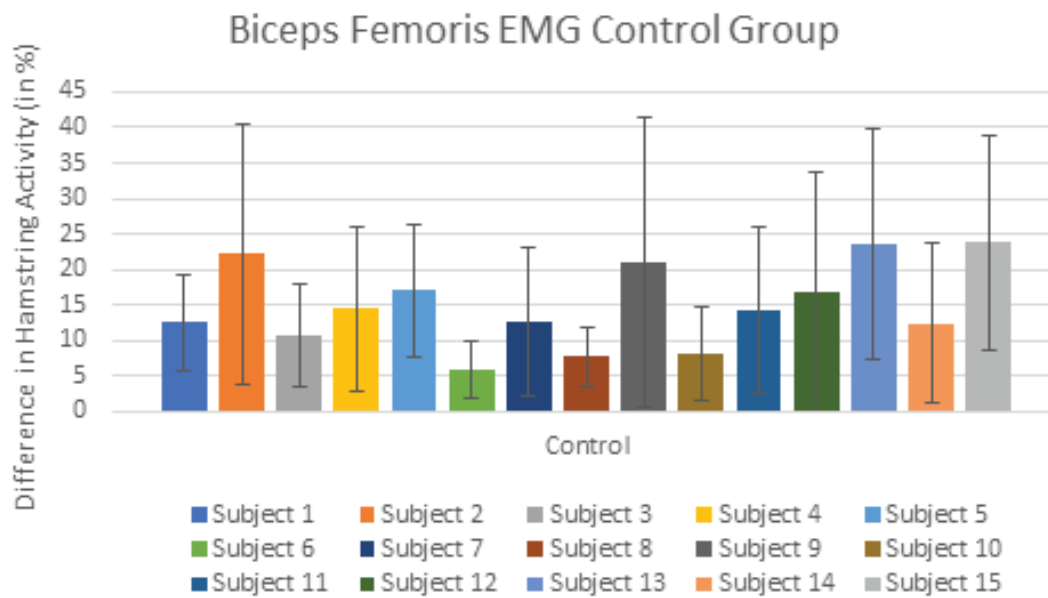


Figure 12. Control Group Biceps Femoris Activation during Chair Squat.

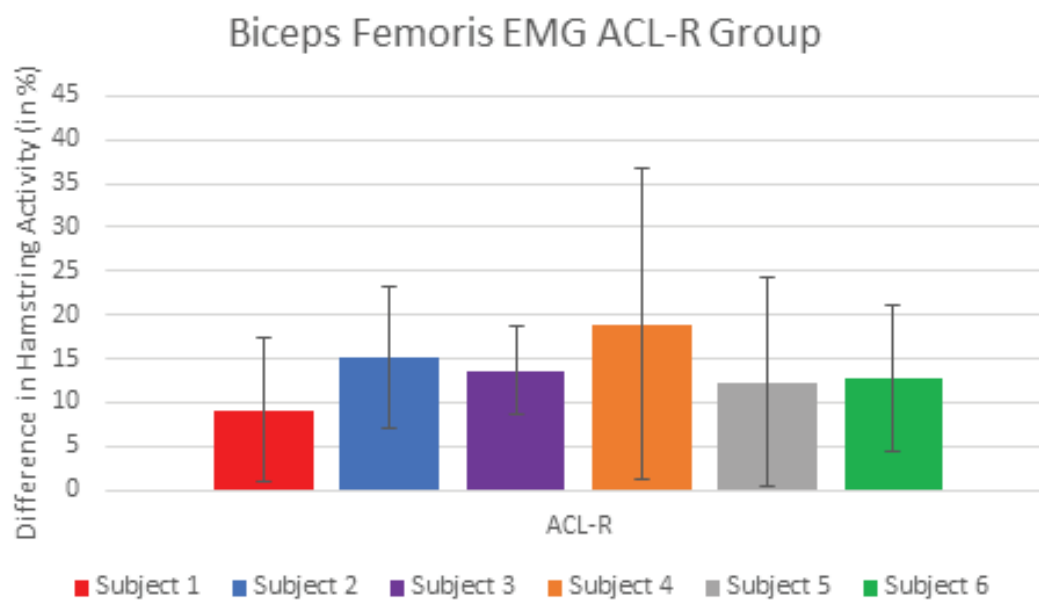


Figure 13. ACL-R Group Biceps Femoris Activation during Chair Squat.

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 ($p = 0.78$). This can be seen in Figures 14–15.

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

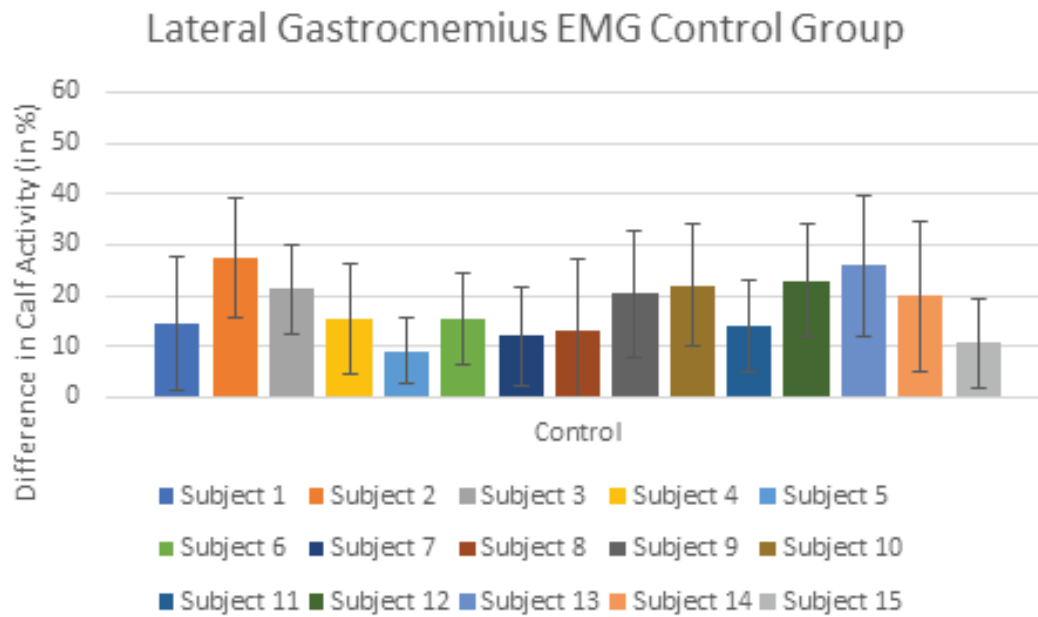


Figure 14. Control Group Lateral Gastrocnemius Activation during Chair Squat.

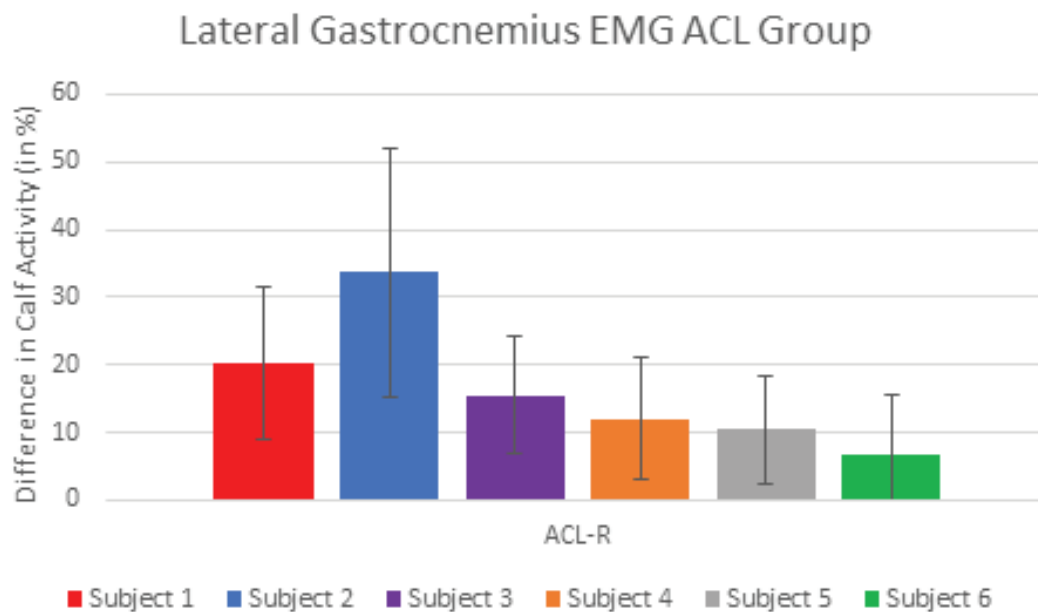


Figure 15. ACL-R Group Lateral Gastrocnemius Activation during Chair Squat.

were averaged and normalized to the maximum value recorded during the trials.

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%. The difference between the two groups was not statistically significant ($p = 0.14$) after a two-tailed t-test. This can be seen in Figures 16–17.

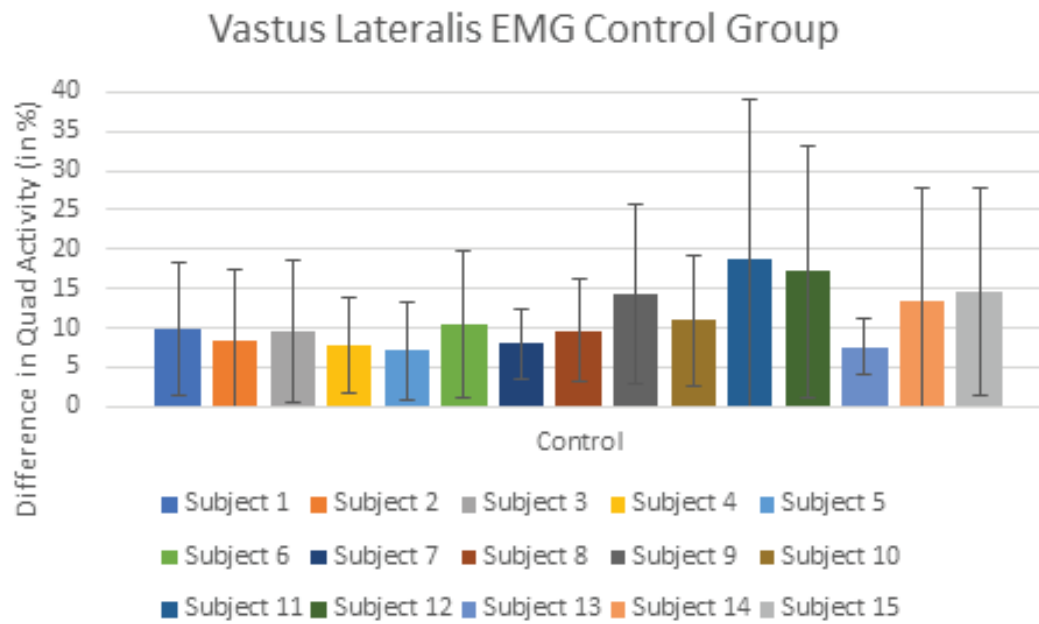


Figure 16. Vastus Lateralis Activation during Sit-to-Stand Activity (Control Group).

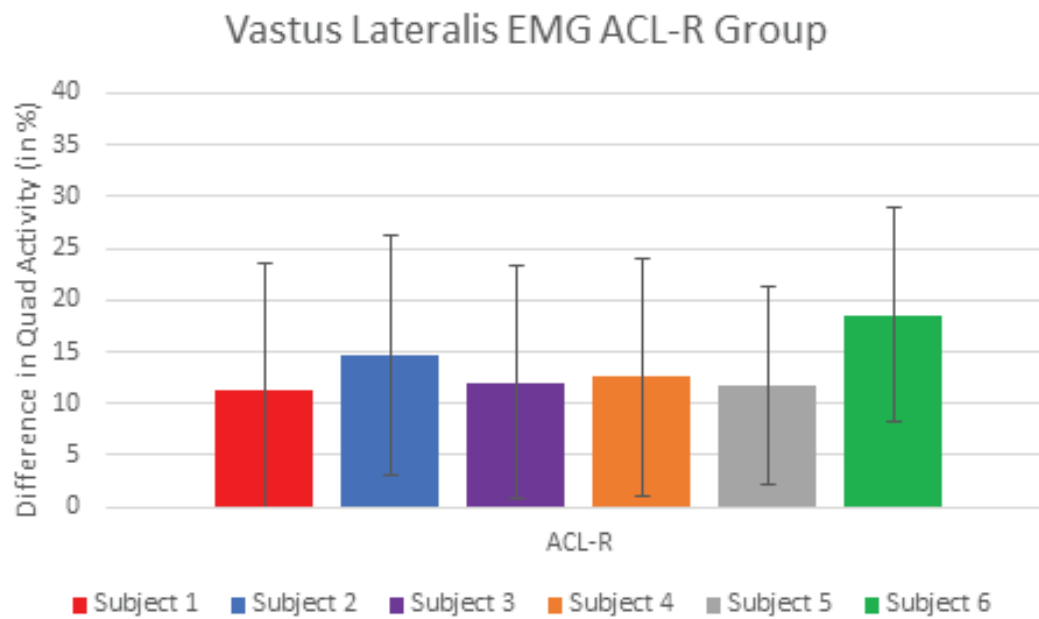


Figure 17. Vastus Lateralis Activation during Sit-to-Stand Activity (ACL-R Group).

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 ($p = 0.84$). This can be seen in figures 18–19.

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

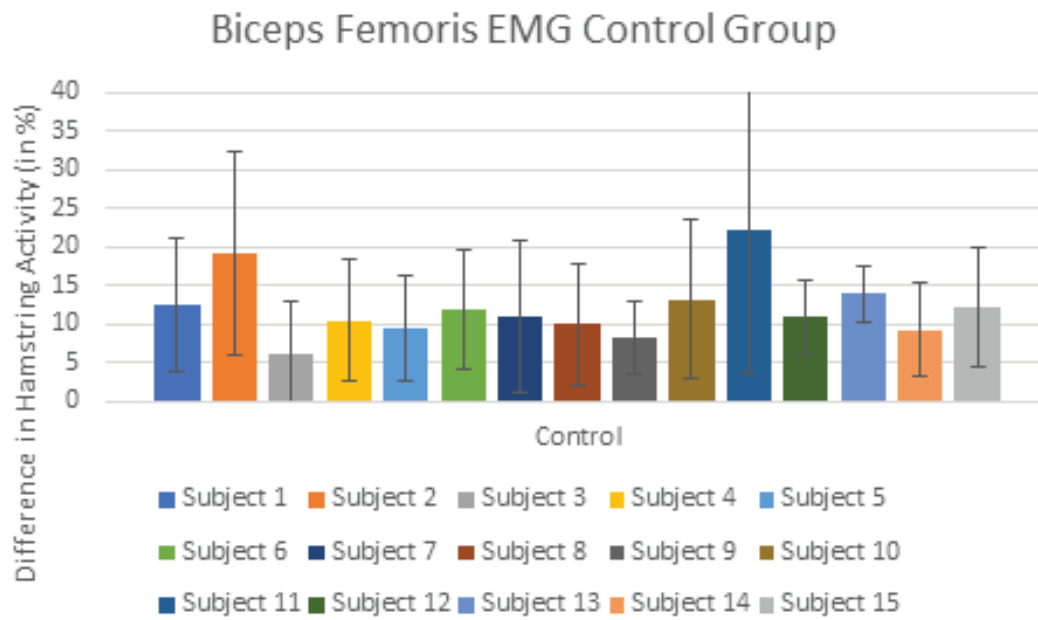


Figure 18. Biceps Femoris Activation during Sit-to-Stand Activity (Control Group).

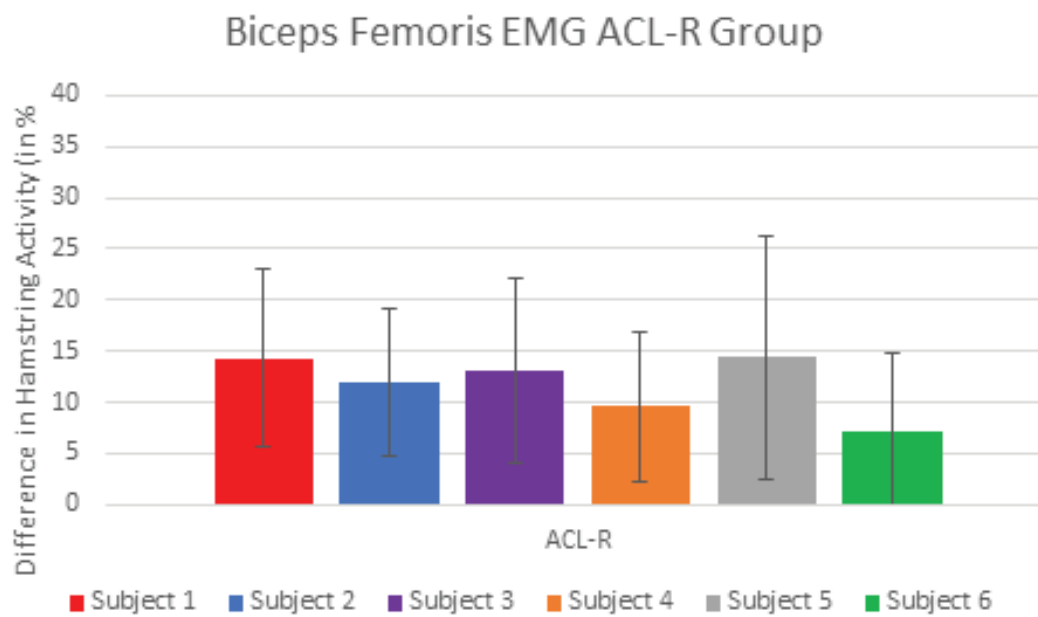


Figure 19. Biceps Femoris Activation during Sit-to-Stand Activity (ACL-R Group).

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 ($p = 0.19$). This can be seen in Figures 20–21.

The last part of the EMG analysis involves using the data collected from the treadmill exercise. The first comparison that drawn was between the subjects in the control group compared to those in the ACL-R group. Table 9 shows the mean differences in muscle activation that was recorded during the treadmill exercise.

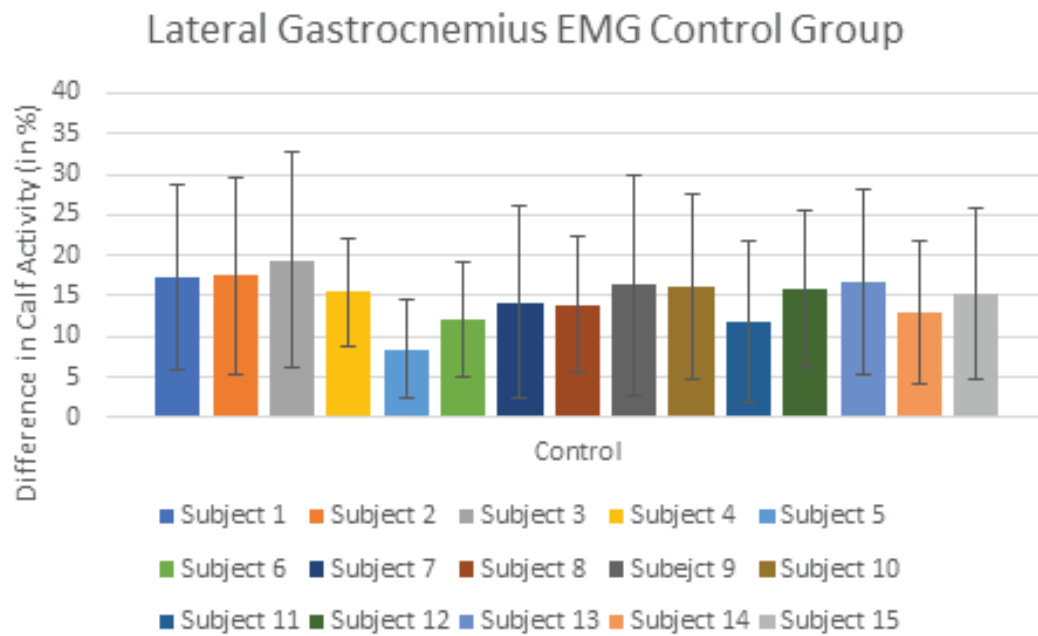


Figure 20. Lateral Gastrocnemius Activation during Sit-to-Stand Activity (Control Group).

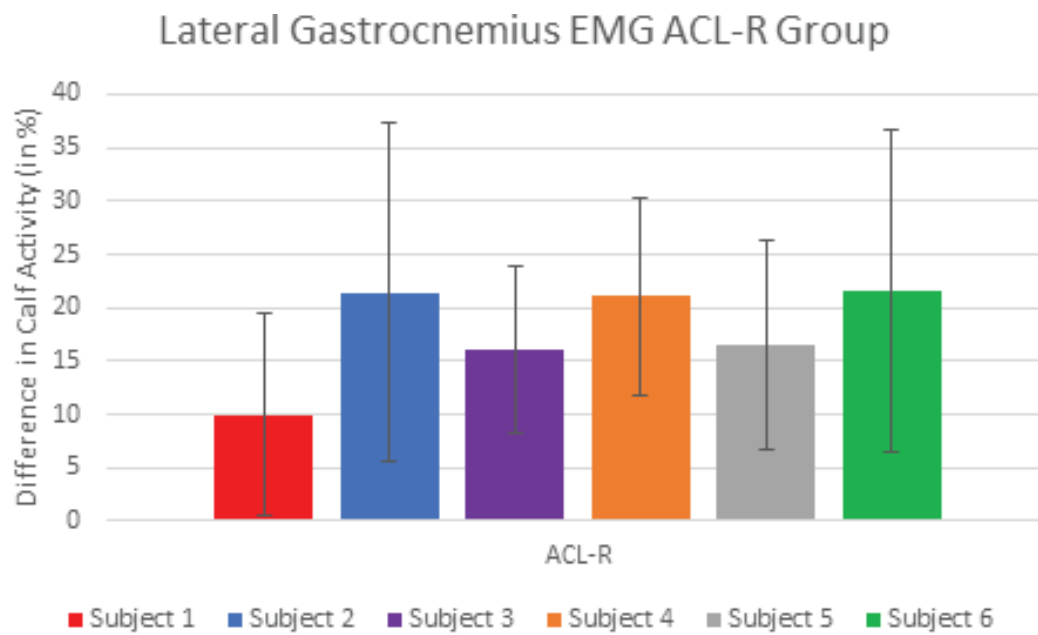


Figure 21. Lateral Gastrocnemius Activation during Sit-to-Stand Activity (ACL-R Group).

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.

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 10. The results below show no statistical differences.

Table 9. Treadmill Mean Muscle Activation Difference Before and After Exercise (Control vs. ACL-R) (*significance at p = 0.05).

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

Table 10. Treadmill Mean Muscle Activation Difference Before and After Exercise (Patellar Graft vs. Hamstring Graft) (*significance at p = 0.05).

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

Conclusions

The study had some interesting results that should definitely be 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. Though there were no statistically significant differences, minor variations suggest that 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. This study had some limitations. First, as previously mentioned, the sample size of the study was limited due to poor follow up of subjects enrolled in the study. Second, the age range of the study was limited to college students. Older or younger subjects may show different trends during the rehabilitation process. Lastly, the study was non-randomized. It may be beneficial to conduct a research study using two groups, one that uses the real-time feedback and the other who follows a typical rehabilitation protocol.

ACL injuries have become commonplace in sports thus making it imperative to develop effective physical therapy techniques and return to sport protocols 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.

REFERENCES

- (2015). *Anterior Cruciate Ligament (ACL) Injuries: Topic Overview*. Available: <http://www.webmd.com/a-to-z-guides/anterior-cruciate-ligament-acl-injuries-topic-overview>.
- Zeller BL, McCrory JL, Kibler WB, Uhl TL** (2003) 'Differences in Kinematics and Electromyographic Activity Between Men and Women during the Single-Legged Squat.' *The American Journal of Sports Medicine*, 31, pp. 449–456.
- Fryar CD, Gu Q and Ogden CL** (2012) 'Anthropometric reference data for children and adults: United States', 2007–2010. *Vital Health Stat*, 11.
- Huber J, Lisiński P, Kłoskowska P, Gronek A, Lisiewicz E, Trzeciak T.** (2013) 'Meniscus suture provides better clinical and biomechanical results at 1-year follow-up than meniscectomy.' *Arch. Orthop. Trauma Surg.* 133 (4), pp. 541–9.
- Lewek M, Rudolph K, Axe M, Snyder-Mackler L** (2002) 'The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction.' *Clinical Biomechanics*, 17, pp. 56–63.
- Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR and Paletta GA** (2014) 'Incidence and Trends of Anterior Cruciate Ligament Reconstruction in the United States.' *American Journal of Sports Medicine*, 42, pp. 2363–2370.
- Massachusetts General Hospital** (2015) 'Exercises after injury to the Anterior Cruciate Ligament (ACL) of the Knee.'
- Suresh M, Bowen S, Mathioudakis A, Gielo-Perczak K.** (2018) 'Effects of a short-term, high intensity plyometric training regimen on postural control of young adults.' *Issue Rehabil. Orthop. Neurophysiol. Sport Promot.* 25, pp. 7–20.