Spring 2018

EEG and EMG Sensorimotor Measurements to Assess Proprioception Following ACL Reconstruction

Teagan Frances Northrup

Recommended Citation

Northrup, Teagan Frances, "EEG and EMG Sensorimotor Measurements to Assess Proprioception Following ACL Reconstruction" (2018). *Honors Theses and Capstones*. 389.
https://scholars.unh.edu/honors/389

EEG and EMG Sensorimotor Measurements to Assess Proprioception Following ACL Reconstruction

Teagan Northrup

tfn2000@wildcats.unh.edu

University of New Hampshire

College of Engineering and Physical Sciences

Department of Electrical and Computer Engineering

Advisors:

Dr. Wayne Smith Department of Electrical and Computer Engineering

Dr. Ronald Croce, Department of Kinesiology

Contents

Introduction

The Anterior Cruciate Ligament (ACL) is the primary source of stability in the knee; its role is to prevent the tibia from sliding in front of the femur which provides rotational stability [1]. When the ACL is torn, it typically must be repaired through reconstructive surgery. After an ACL reconstruction, it has been widely documented that patients suffer from proprioceptive deficiencies in the knee. Proprioception is defined as “the specialized variation of the sensory modality of touch that encompasses the sensation of joint movement and joint position” [2]. Essentially, proprioception is very important in helping an individual understand where their knee is in space and sensing movement. For example, when an individual senses a change in their balance there is a communication exchange between their muscles and neural network. The sensory receptors in the knee send signals through the spine to the brain, indicating that there has been motion. The immediate involuntary response tells the muscles to return the knee to its original position. A secondary response allows the motor cortex of the brain to interpret the sensation and involuntary movement and instructs the muscles on how to respond. This two-step proprioceptive process allows individuals to adjust to changing situations to maintain balance while standing, walking or running. Therefore, effective proprioception is an important indicator of recovery for an individual with an ACL reconstruction.

Currently, one problem doctors and physical therapists face in working with individuals who have ACL reconstructions is that they do not have adequate tools to assess progress in proprioception to help decide when a person can return to normal or strenuous activity. In addition to the lack of effective measurement tools, another problem is there is not a clear understanding of how proprioception changes after ACL reconstruction surgery. It is not known whether there is a specific pattern of progressive improvement in proprioception or a time at which a patient’s proprioceptive response becomes stable. The goal of this project is to develop a way to measure proprioception using signal processing to observe changes over time.

For the purpose of this study, proprioceptive responses will be measured using an electromyogram (EMG) and an electroencephalogram (EEG). The procedure will use a platform perturbator to serve as the stimulus. An individual will stand on the platform perturbator; the platform is controlled to move slightly forward or backward. The individual will have EEG and EMG sensors to measure the individual’s response each time the perturbator moves.

Background

The knee is a complex joint that is a combination of different structures including bones, ligaments, and tendons. The main ligaments and bones of the knee are shown in Figure 1. Three bones converge in the knee including the femur (thigh bone), the tibia (shin bone), and the patella (knee cap). The four ligaments in the knee connect the bones and provide stability within the knee. There are two collateral ligaments which lie along the sides of the knee and provide side-to-side stability and two cruciate ligaments on the interior of the knee joint. The medial collateral ligament is on the inside and connects the femur to tibia; the lateral collateral ligament is on the outside of the knee and connects the femur to the fibula. The cruciate ligaments cross diagonally connecting the femur to the tibia and provide front to back stability. The anterior cruciate ligament is in front of the posterior cruciate ligament and prevents the tibia from sliding in front of the femur and provides rotational stability [1]. The primary focus of this study is the role of the anterior cruciate ligament (ACL) in proprioception, particularly after an ACL reconstruction.

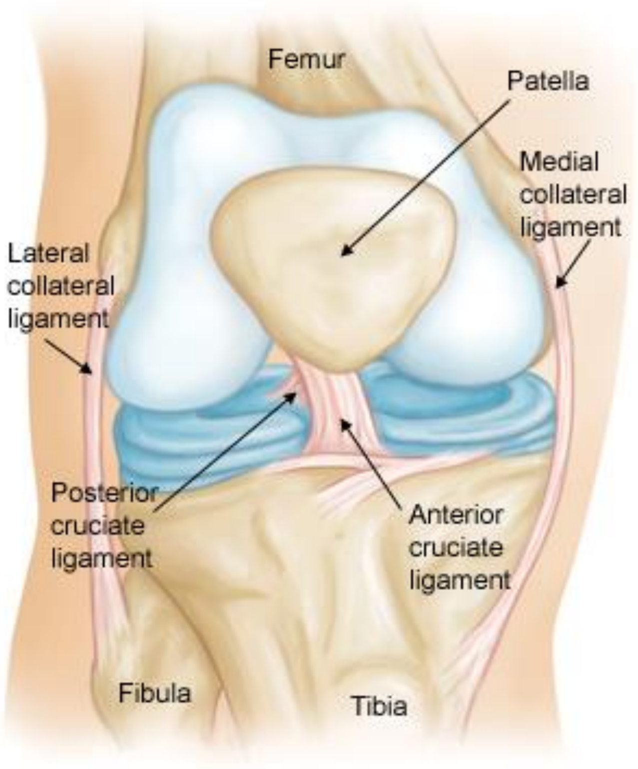


Figure 1. Ligaments and Bones of the Knee

There are two ways to obtain an ACL injury, a contact injury or a non-contact injury. Seventy percent of ACL injuries occur from non-contact injuries and commonly occur when someone is decelerating, landing, or pivoting [3]. A contact injury occurs from a direct hit to the knee. Most ACL injuries result in complete or near complete tears meaning the ACL is split into two pieces leaving the knee unstable [1]. Due to the higher number of males participating in sport related activities there are more ACL injuries in men [3]. It has been widely documented, however, that women have a significantly higher risk of ACL injuries. There has been extensive research examining a number of potential factors. According to the American Academy of Orthopedic Surgeons some of the risk factors for women include muscle strength, neuromuscular control, pelvis to knee angles, ligaments laxity, and fluctuation of estrogen levels[9].

Irrespective of gender, partial and complete tears are typically repaired through surgical reconstruction. The traditional ACL reconstruction surgery consists of removing the injured ACL and replacing it with a graft which is attached to the femur and the tibia. There are two types of ACL grafts which include allografts (from a cadaver) and autografts (from the patient). Grafts are most commonly from the patella tendon or the hamstring but are occasionally harvested from the quadriceps. There is a 90% success rate for ACL reconstruction surgery related to knee stability, patient satisfaction, and return to activity [4]. While the surgery is very successful, the risk of a subsequent ACL injury on either leg increases from 1 in 3,000 (prior to injury) to 1 in 50 (after the initial injury).

One of the suggested reasons for the increased risk for ACL re-injury is the proprioceptive deficits that result from ACL reconstructive surgery. Proprioception is defined as "the specialized variation of the sensory modality of touch that encompasses the sensation of joint movement and joint position" [5]. There have been many studies looking at the relationship between participants with ACL reconstructions and proprioceptive deficits. Studies have documented that ACL reconstructed knees have deficits not only in proprioception, but also in muscle strength, explosive strength, and gait[6], [7], [8], [9], [5]. One implication of proprioceptive deficits is an altered gait after surgery due to the ACL "relearning" its function. Proprioception plays a large part in the stability of the knee and knowing the position of the joint, which is critical to replicating one's pre-injury gait. Proprioception is also necessary to detect movement and acceleration. Proprioception is part of a closed loop activity between the knee and brain (via the central nervous system) that starts the reflex response and regulates the muscles. Some studies have investigated brain activity to determine the reasons for proprioceptive differences in ACL reconstructed knees [6], [10]. In addition, the ACL contains mechanoreceptors that are used as a communicator within the central nervous system, which is what controls those responses. The majority of mechanoreceptors in an ACL reside at the ends of the ligament near the femur and tibia and make up 2.5% of the ligament [11]. After the ACL reconstruction surgery when the original mechanoreceptors are no longer present, the neural communication system has to be reestablished with the new graft. Over time, neural communication improves but it may never recover to the pre-injury state; this differential leads to proprioceptive deficits.

Based on the existing literature, proprioception is typically measured using Joint Position Sense (JPS) testing and Time Threshold to Detection of Passive Motion (TTDPM). A meta-analysis focused on ACL injuries and the effect on proprioception only identified studies using JPS and TTDPM [5]. JPS was defined as passively moving a joint to a specific angle and then the participant actively reproduces the same angle. The difference in position can then be measured as the error. A typical JPS setup is shown in Figure 2. TTDPM is defined as a measurement of the passive movement angle before the movement can be detected by the participant [5]. While the results of both measures quantify proprioception, they don't reflect the sense of force or movement [6]. In addition, both methods are artificial and not applicable to real world circumstances which have many more factors that influence an individual's response and reaction. JPS is limited in the sense that it relies only on a single biomechanical parameter [6] and neglects timing. There are even fewer studies that use TTDPM and many of those studies also use JPS.

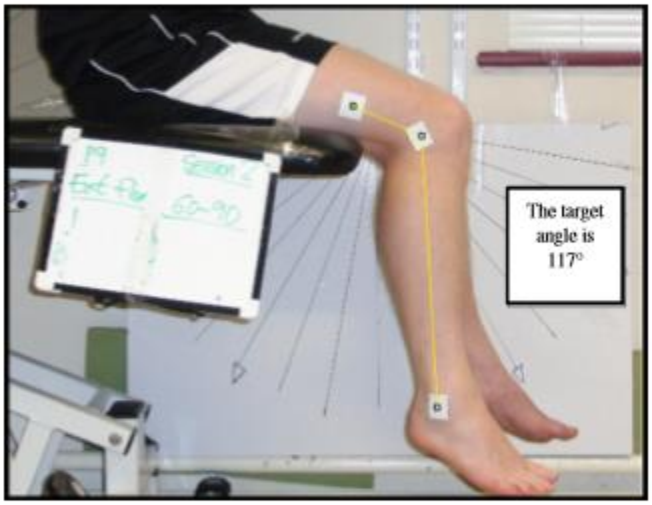


Figure 2. Typical Joint Position Sense Test Set-up for the Knee Joint

To expand on existing research of ACL injuries and proprioception, there have been some studies that concurrently look at brain activity. One study used electroencephalogram (EEG) to look at the areas of brain activity and electromyogram (EMG) to look at muscle activity around the knee [6]. This study found that patients with ACL reconstruction had a significantly higher frontal Theta power compared to the healthy control group. Frontal Theta power is a measure of brain activity in the frontal lobe and is higher when participants "engage in complex attention-demanding tasks" [6, pp. 481]. This suggests that there was more brain activity in the frontal lobe with the ACL group, which indicates a higher level of attention during the JPS test. It was also reported that participants with ACL reconstruction not only showed increased theta power from the EEG while testing the ACL injured leg, they also showed higher theta power during testing of the uninjured leg. This suggests that using the uninjured leg may not be a sufficient control in studies or clinical practice.

Based on the existing literature, the goal of this project was to develop an improved method to measure proprioception using signal processing and applied this method to observe differences in proprioception after an ACL reconstruction. This project compared the proprioception of individuals who had a recent ACL reconstruction with individuals with no knee injuries. In addition for individuals with an ACL reconstruction, the reconstructed knee was compared to the healthy knee.

Methods

Participants

The participants for this study were volunteers who were recruited though flyers around the University of New Hampshire campus or through word of mouth. There were 8 female participants in this study, 6 of the participants had healthy knees and participated in a single testing session. Two 2 additional participants engaged in repeated measurements engaging in 3 testing sessions approximately 2 weeks apart. Of the two participants who engaged in repeated testing, one participant was had healthy knees and the other had had an ACL reconstruction 14 months prior to the start of testing.

The study procedure was approved by the Institutional Review Board (IRB) and all of the participants signed a consent form that laid out the testing procedure and participation expectations. Participants were allowed to stop at any point during the testing or could decide to not participate in subsequent testing dates. All of the participants who began the testing procedure participated fully.

Equipment

Testing and data collection took place in the Biomechanics & Motor Control Lab in New Hampshire Hall at the University of New Hampshire. This study used the existing EEG and EMG setup in that lab used for ongoing projects. In addition, a platform perturbator provided forward and backward movement as a stimulus to which participants reacted. More detailed discussion of the equipment used follows.

Platform Perturbator

A platform perturbator was used to offset one's balance by quickly jolting the platform the subject was standing on. An electric linear actuator was attached to the base and was used to push and pull the platform. A DC voltage supply powered the actuator while a power metal-oxide-semiconductor field-effect transistor (MOSFET) (IRL520) was used to control it. A trigger was generated by the researcher that sent a signal to the gate lead of the MOSFET to turn it on, which then turned on the actuator. Rollers were placed below the platform and used as linear motion guides to reduce the frictional force added from the weight of the subject [12]. The platform perturbator moved one inch per second for a duration no longer than half a second. As the subject regained their balance, the perturbator remained idle until it received another signal to perturbate the subject backwards. The platform perturbator was controlled using an H-bridge circuit, shown in Figure 4, which allowed the researcher to use a controller to move the platform forward and backwards without manually changing the power supply.

Figure 3. Platform Perturbator

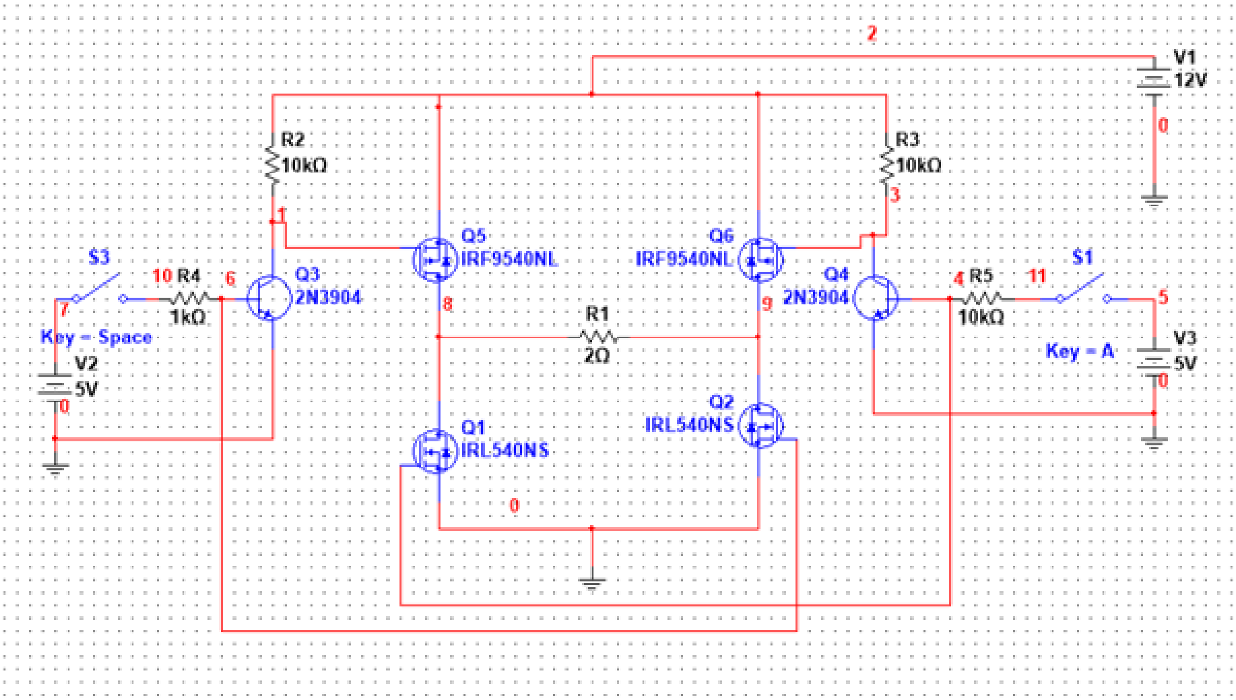
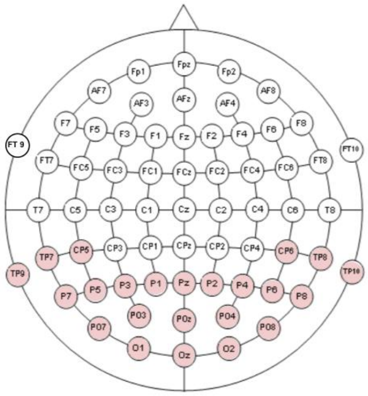


Figure 4. H-Bridge Switch Circuit

Electroencephalogram (EEG)

EEG is used to measure the activity of the brain using surface electrodes on the scalp. There are 4 frequency bands that are usually measured with EEG: delta (<4 Hz), theta (4-7 Hz), alpha (8-13 Hz), and beta (14-50 Hz). Delta frequencies are generally seen during sleep, theta frequencies are seen during disappointment, frustration, and meditation, alpha frequencies are prominent during a resting period with eyes closed, and beta frequencies are seen during intense mental activity with eyes open [13]. For this study, EEG signals were measured using the

BrainVision^{TM} software and a 64 channel EEG cap (see Figure 5) for event related potentials corresponding to our stimulus. An event related potential (ERP) is the measured brain response directly related to a specific sensory, cognitive, or motor event.



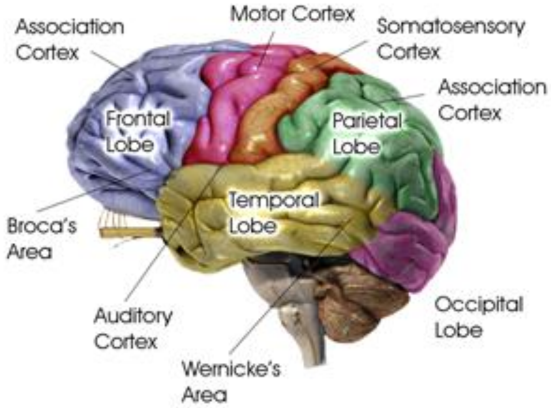


Figure 5. Layout of 64 Channel EEG Cap

Figure 6. Areas of the Brain

The areas of the brain that were observed included the motor cortex and the somatosensory cortex. The motor and somatosensory cortices are shown in Figure 6 near the middle of the brain. These areas were monitored with a 64 channel EEG cap similar to the one in Figure 5, to look at ERPs. The ERPs we were looking for happen around 300ms after the stimulus corresponding with information coming into the brain and leaving the brain in response to the small movement stimulus.

Electromyogram (EMG)

EMG is used to assess the health of muscles and the motor neurons that control them. The motor neuron sends an electrical signal to the muscle resulting in muscle contraction [14]. An electromyogram uses electrodes to detect the summated electrical activity of muscle cells. The signals obtained from the EMG are able to determine the timing of the muscle reactions. To best determine the reaction, EMG signals can be obtained from two different leg muscles: tibialis anterior and gastrocnemius. Figure 7 shows the electrodes placement for each muscle.

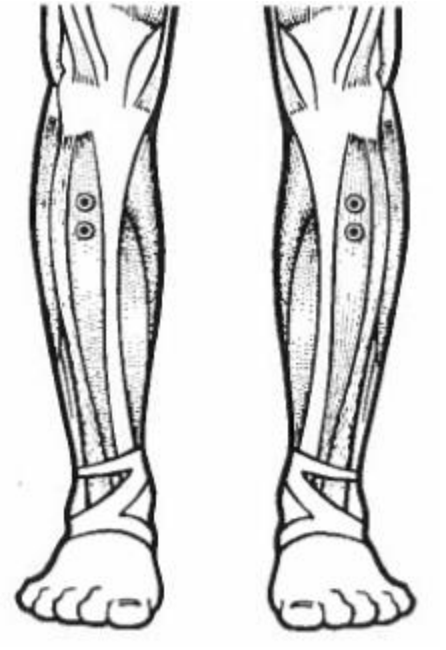


Figure 7a. Tibialis Anterior Muscle

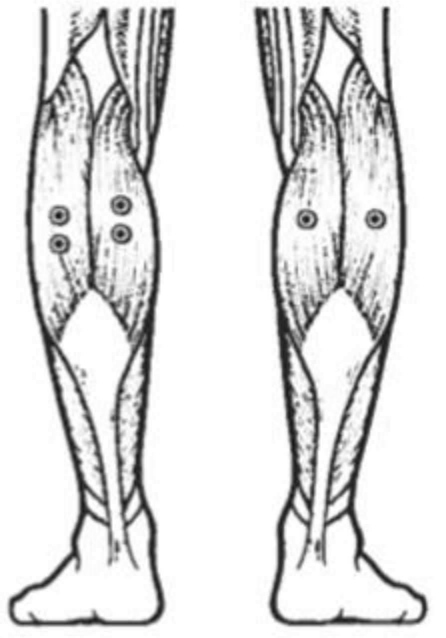


Figure 7b. Gastrocnemius Muscle

Measures

For the purpose of this study, proprioceptive responses were measured using an electromyogram (EMG) and an electroencephalogram (EEG). The procedure used a platform perturbator to serve as the stimulus. An individual stood on the platform perturbator; the platform was controlled to move slightly forward or backward. The individual had EEG and EMG sensors to measure the individual’s response each time the perturbator moved.

The EEG monitored the brain activity and the EMG monitored the activity of the muscles around the knee. The EMG allowed us to see two different muscle responses, the muscle activation onset and the peak. The onset was when the muscles initially contract and that comes from the involuntary response from the spinal cord. When the platform moved the knee sent a signal through the spinal cord. There was an initial response signal that returned directly to the knee from the spine, this resulted in the EMG onset. The EMG peak response came from the second signal sent back to the knee, this signal continued up the spinal cord to the brain, specifically the motor cortex. The motor cortex decided how to respond to the sensation and sent a signal back to the muscles around the knee with instructions, this muscle response corresponded with the EMG peak. By comparing the timing of the EMG responses (onset versus peak) we determined how long it takes for the spinal response and the processing response from the brain. This comparison of responses is illustrated in Figure 8 where the yellow path is the involuntary response from the spinal cord directly back to the knee which corresponds with EMG onset and the red path shown is the response that goes from the knee to the brain which sends a signal back to the knee telling it what to do, corresponding to EMG peak.

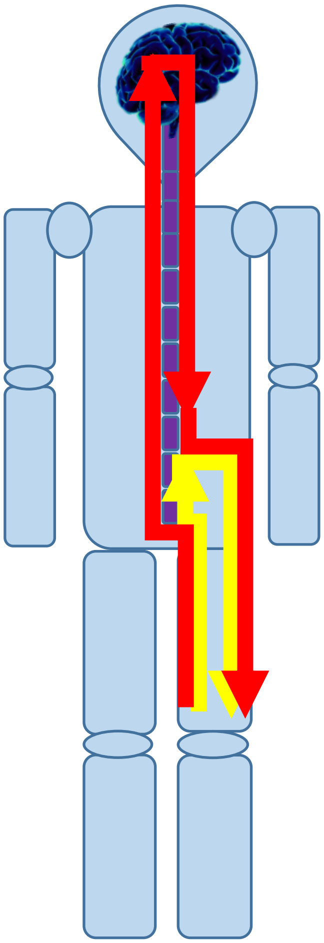


Figure 8. EMG Peak vs EMG Onset

Along with the EMG timing, we used the EEG data to observe the brain activity during this process. By specifically looking at the electrodes over the motor cortex we were able to determine when information was received by a certain area of the brain and when information was being sent out from that area. By using both EEG and EMG measurements, we were able to track the response time from the movement of the perturbator in relationship to the neural and muscular response. This combined approach allowed the entire proprioceptive response to be measured through signal processing and data analysis. Figure 9 shows a block diagram of the test setup.

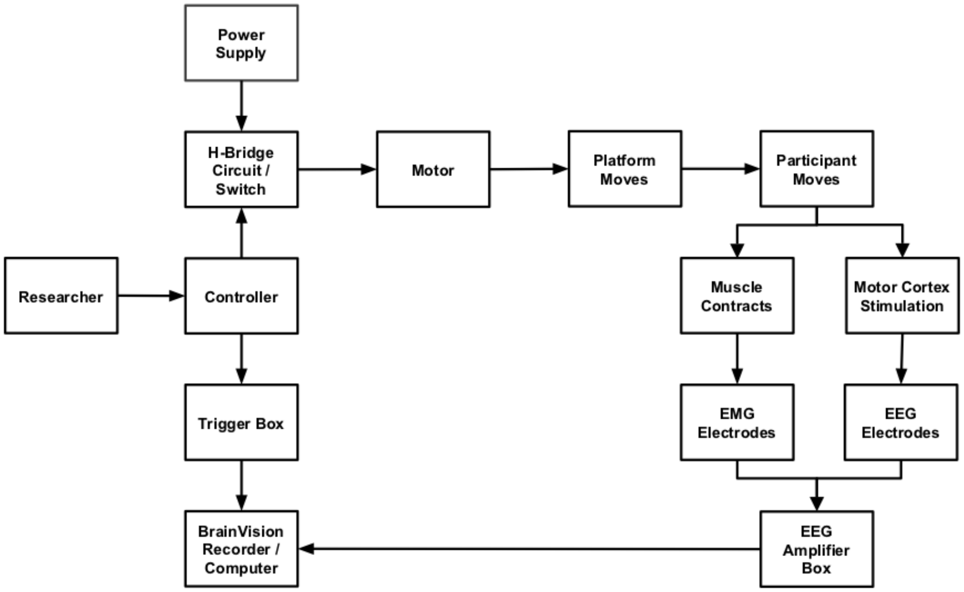


Figure 9 Block Diagram of Test Setup

Procedure

Participants came to the Biomechanics & Motor Control Lab in New Hampshire Hall at a mutually convenient time. Participants were given a thorough explanation of the study and read and signed the informed consent. Participants were given a brief questionnaire asking questions about any injuries, dominant leg, and other demographic questions. A copy of the questionnaire is included in the Appendix.

The EMG was used to measure the level of muscle electrical activity of the Anterior Tibialis (AT) and Medial Gastrocnemius (MG). Silver/silver chloride pre-gelled surface electrodes were placed 2.5 cm apart and parallel to the muscle fibers over the longitudinal midline between the motor point and the tendon. Thorough skin preparation for electrode placement included removal of dead epithelial cells with a razor, isopropyl alcohol, and an abrasive pre-gel (Nuprep abrasive preparation gel). The skin was cleaned and abraded to achieve skin impedance of less than 10-kΩ.

For the EEG, the participants head circumference was measured to best fit a 64-channel EEG cap. Gel was applied to each electrode site with a blunt needle (which additionally slightly abrades the scalp to improve impedance) until an impedance of less than 25-kΩ was reached.

Each participant stood barefoot on the platform perturbator with feet hip width apart. Earbuds were worn to drown out the motor actuator prior to the platform perturbator moving so that the participant cannot anticipate the movement. To allow each leg to be individually tested, the leg tested had the foot firmly planted on the platform while only the toe of the other foot was touching to help with balance. A high-rise table was next to the platform perturbator in the off chance the participant lost balance. EMG and perturbator data was synchronized with EEG data via auxiliary inputs into the EEG system hardware. EEG, and EMG data were recorded and analyzed using the BrainVision^{TM} Recorder and Analyzer Software.

One trial consisted of the participant being perturbated forward at a speed of one inch per second for a random duration (200 to 800 ms), and then moved backwards once balance had been regained. Perturbation timing was randomized between 0.5 and 5 seconds to reduce the participant's anticipation of the platform movement. For each participant, 100 accurate responses were taken with either two-minute standing or sitting breaks every 25 trials to prevent muscle fatigue.

The procedure for recording measurements:

1. Start recording on the BrainVision^{TM} Recorder software
2. Save file for new subject with the leg being tested and the testing date
3. Participant stands on the one leg being tested with the other leg just for balance
4. Remain standing for 25 trials forwards and 25 trials backwards
5. 2 minute break so the participants legs don't get fatigued
6. 25 trials forward/25 trials backwards
7. 2 minute break
8. 25 trials forward/25 trials backwards
9. 2 minute break
10. 25 trials forward/25 trials backwards
11. Stop recording
12. Remove EMG from tested leg
13. Clean EMG electrodes
14. Set up EMG electrodes on other leg
15. Reevaluate EEG impedances
16. Reapply gel to EEG electrodes if necessary
17. Start recording on the BrainVision^{TM} Recorder software for other leg
18. Save file for new subject with the leg being tested and the testing date
19. 100 trials forward and 100 trials back with 2 minute break every 25 trials
20. Stop recording
21. Remove EEG cap
22. Remove EMG electrodes

Data Analysis

Data analysis was performed using BrainVision^{TM} Analyzer on the raw data recorded from the BrainVision^{TM} Recorder.

Remove Channels: First the EEG channels that were not used were removed and the EEG data was sorted to remove bad trials.

Filter: All remaining EEG signals were bandpass filtered at 0.1 Hz to 50 Hz and EMG data at 10 to 200 Hz. All data was notch filtered at 60 Hz to remove sinusoidal noise.

Ocular Correction: Built in algorithm used independent component analysis (ICA) to detect artificial components created by blinks. This step removes and corrects blinks from the EEG data.

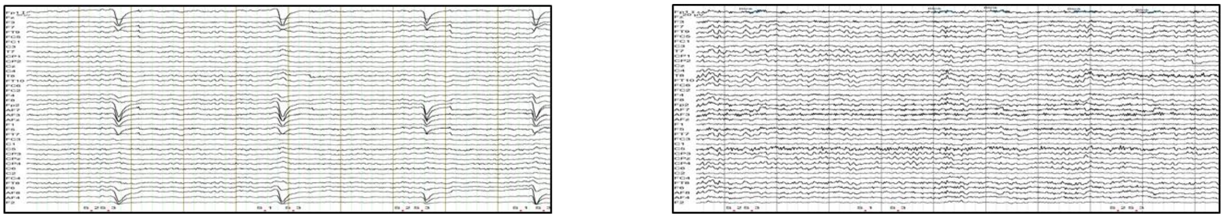

Before Ocular Correction
After Ocular Correction

Figure 10. Before and After Ocular Correction

Segmentation: Data was segmented into 600ms epochs, 200ms pre stimulus to 400ms post stimulus. An epoch was disregarded if the stop trigger did not occur during the desired time frame. Forward and backwards trials were separated and treated as separate data sets.

Baseline Correction: The average voltage from -200ms to 0ms was calculated and treated as the new 0 voltage. This allowed the signals to have a relative zero point for magnitude.

EMG Onset Search: Built in algorithm found the EMG onset time and the EMG peak time for each trial. This data was exported for further examination. EMG onset occurs at the first sign of muscle activity and the EMG peak occurs at the maximum muscle activity due to the stimulus.

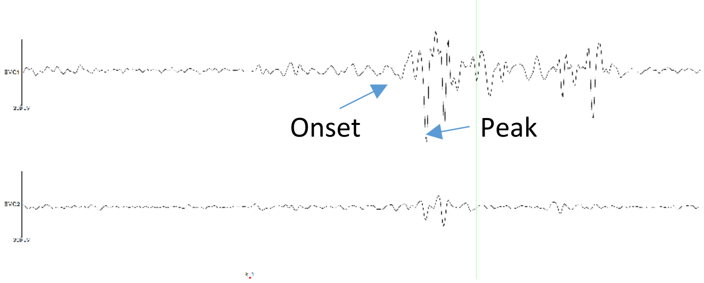
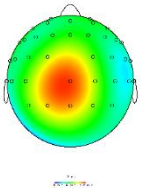


Figure 11. EMG data showing Onset and Peak

Average EMG Onset and Peak: EMG peak and onset data was exported to a spread sheet to determine the average peak and onset time for each subject.

Average EEG: All epochs in a data set were averaged together.

Current Source Density (CSD) Mapping: The built in CSD function performs the spatial second derivative for each electrode relative to the surrounding electrodes. This shows the areas of the brain that has the most activity along with the polarity.



Results

The results presented demonstrate the differences in proprioception between an individual with an ACL reconstruction and healthy controls. Comparisons of two participants will be examined across three measurement periods as well as comparisons between an ACL reconstructed participant to healthy controls with a single measurement period.

Figures 12 and 13 show the EEG data from the Cz electrode which is right above the motor cortex along with the CSD maps corresponding with the EMG Peak and Onset times. These graphs illustrate the relationship between the motor and somatosensory area of the brain and the timing of muscle activity. The EMG peak and onset times are marked on the bottom of the graphs along with the arrows pointing to the Cz data corresponding with those responses. Blue on the CSD map corresponds to a negative current density at Cz and the surrounding area while red corresponds to a positive current density at Cz and the surrounding area. EMG onset corresponds with negative current density (blue) meaning current input to the brain and EMG peak corresponds to positive current density (positive) meaning current output from the brain. Consistent results are shown in both the ACL reconstruction participant and the healthy participant.

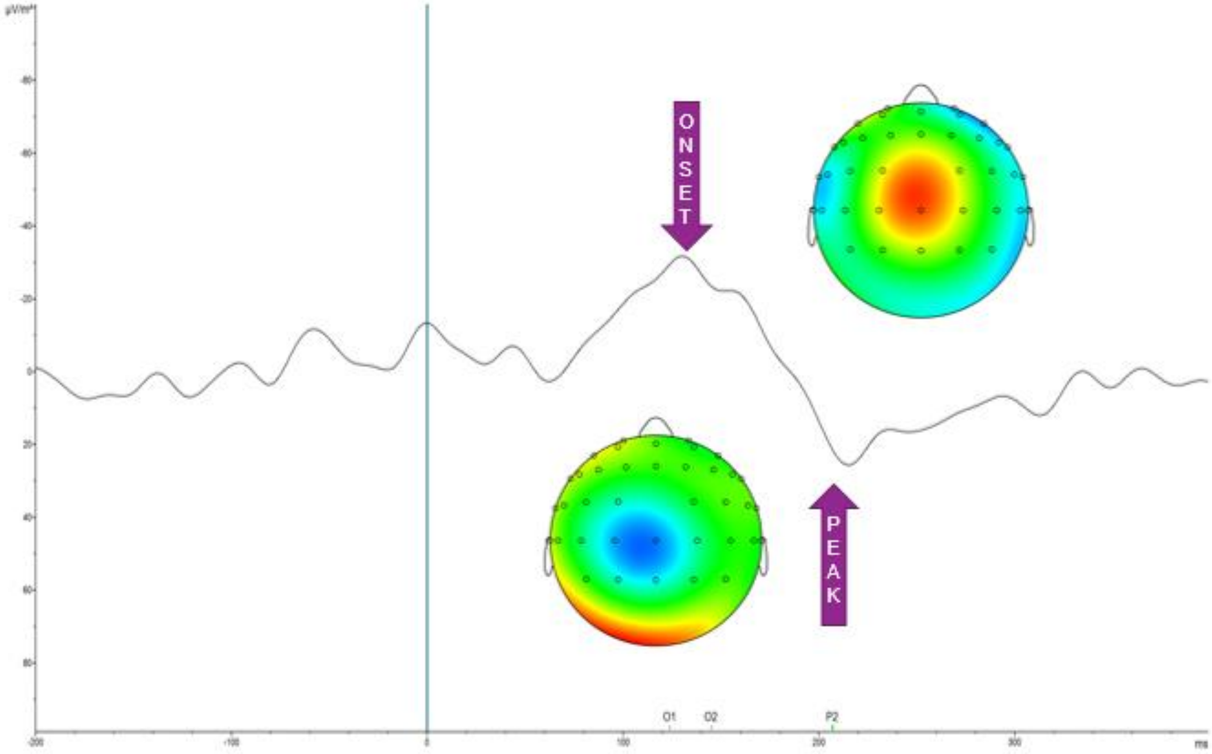


Figure 12. ACL Reconstruction Participant (Right, dominant, reconstructed knee)

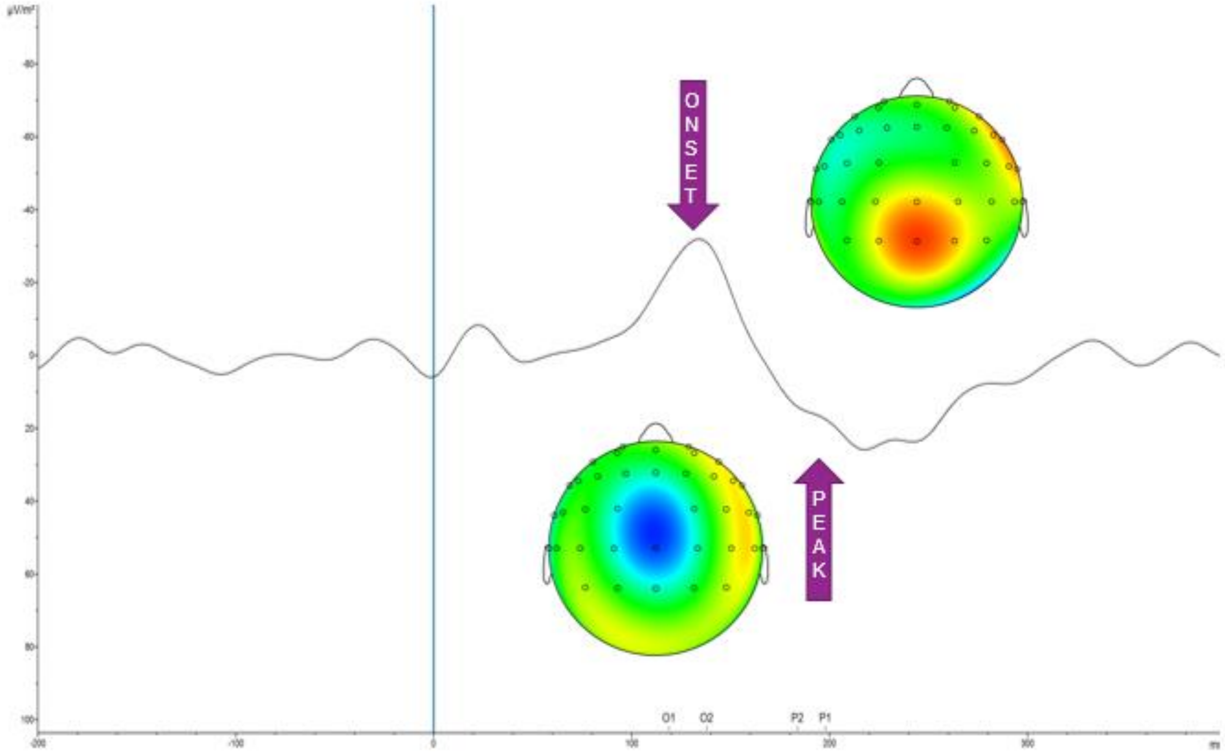


Figure 13. Healthy Participant (Right, dominant, healthy knee)

Figures 14 and 15 show the EMG response timing for two muscles related to the knee and balance, the gastrocnemius (calf) and the anterior tibialis (shin). The onset time refers to the time that the muscle initially contracts which results from the involuntary spinal reaction and the peak time refers to the time of maximum muscle activation, reaction based on feedback from the brain. The graphs depict differences in EMG onset time and EMG peak time for each subject that was tested only once. Table 1 depicts the average peak and onset time for both muscles. It shows that average time between is about 65-70ms which is a very fast response time even though the muscles contract at different times after the stimulus. The 65-70ms time refers to the response time due to the feedback loop within the body between the muscles, nervous system, and the brain.

Table 1. Average Peak and Onset Time

	Gastrocnemius	Anterior Tibialis
Mean Onset	136.99 ms	151.21 ms
Mean Peak	201.30 ms	220.39 ms

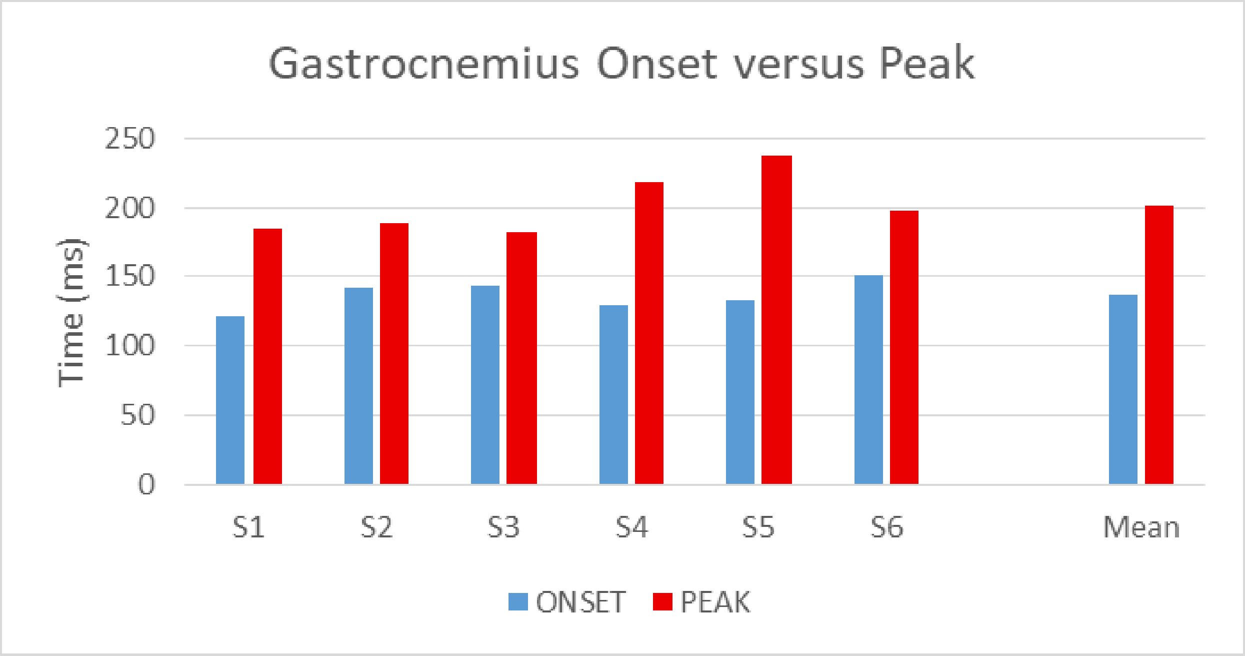


Figure 14. Peak vs Onset Gastrocnemius Muscle

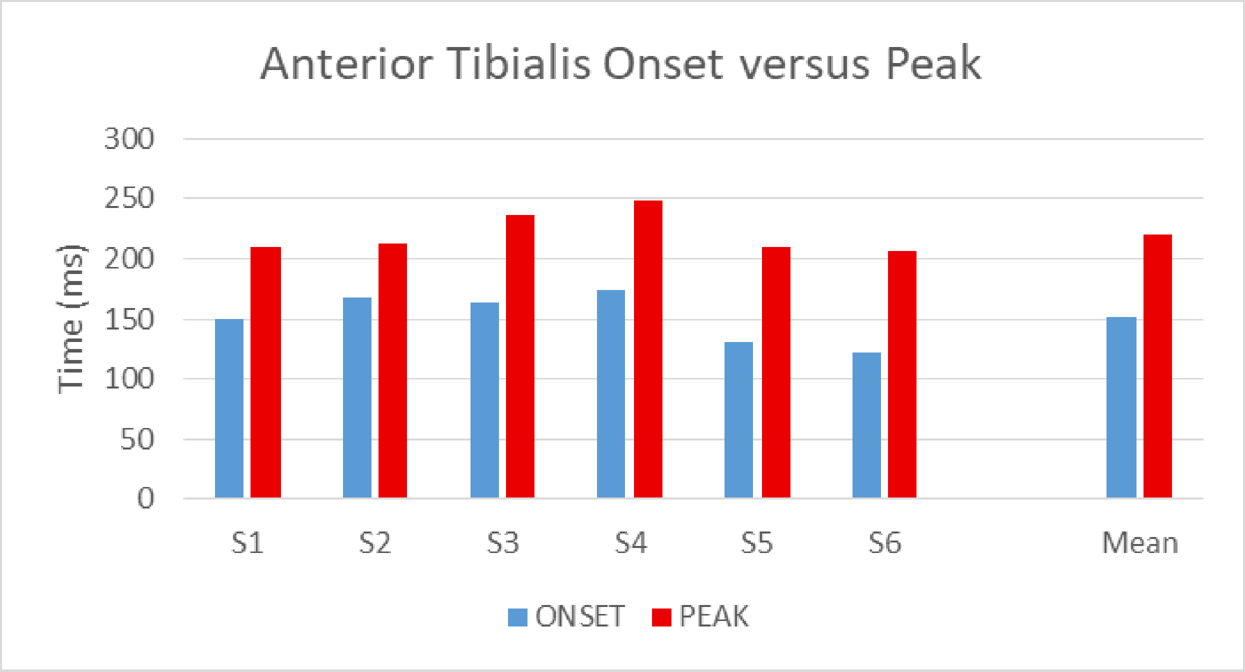


Figure 15. Peak vs Onset Anterior Tibialis Muscle

To determine whether measurement were stable over time, two participants were measured on three occasions. Figure 16 compares the participant with the ACL reconstructed dominant right knee with the healthy participant’s dominant right knee over the three testing times. The graph shows the time between onset and peak which is referred to as the processing time. While there is fluctuation through the three testing periods, averaged over time the ACL reconstructed knee had a longer time between onset and peak, processing time.

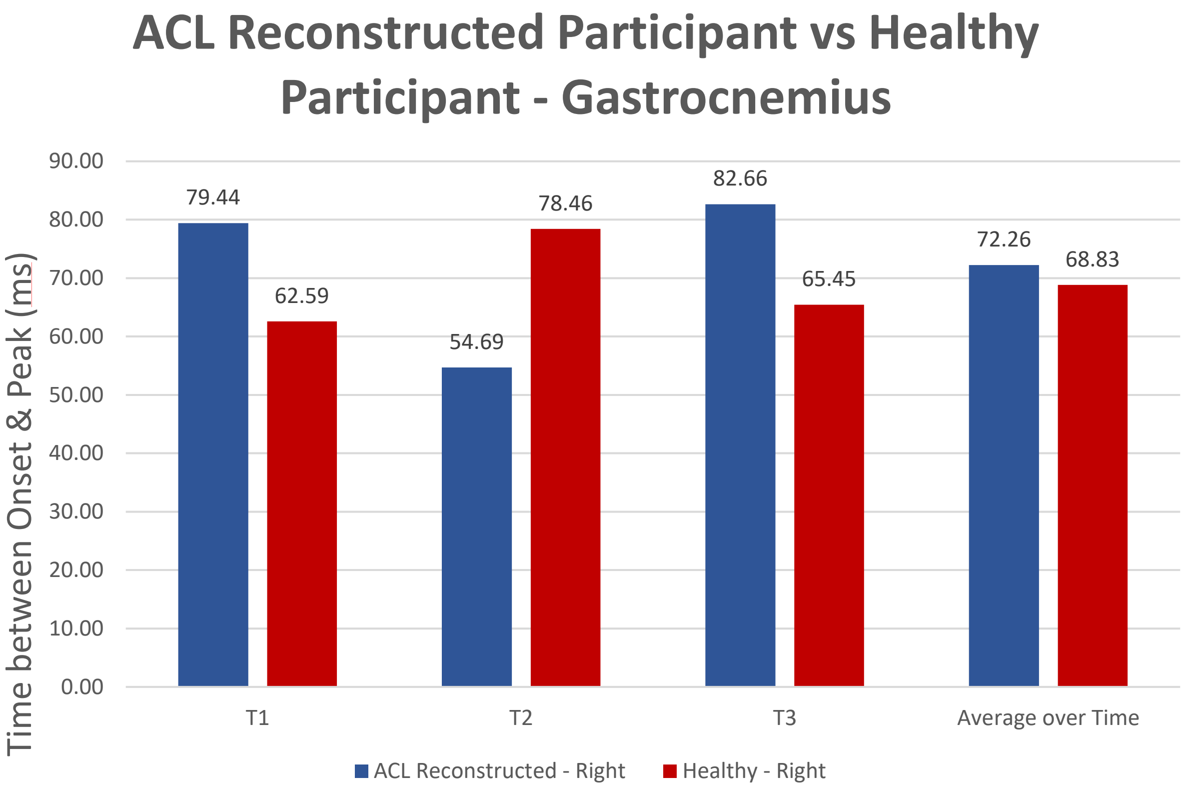


Figure 16. Repeated Measurements – ACL Reconstructed Participant and Healthy Participant

In addition to comparing dominant legs in both the ACL Reconstructed participant and the healthy control participant, Figure 17 compares the right and left knee within the ACL reconstructed participant, using the healthy knee as the control. It shows that there is a longer processing response time in all the anterior tibialis tests and the majority of gastrocnemius tests for the reconstructed knee. Five out of 6 tests had longer response times for the ACL reconstructed participant compared to the healthy control. This suggests that proprioception requires more cognitive processing when using the ACL Reconstructed knee.

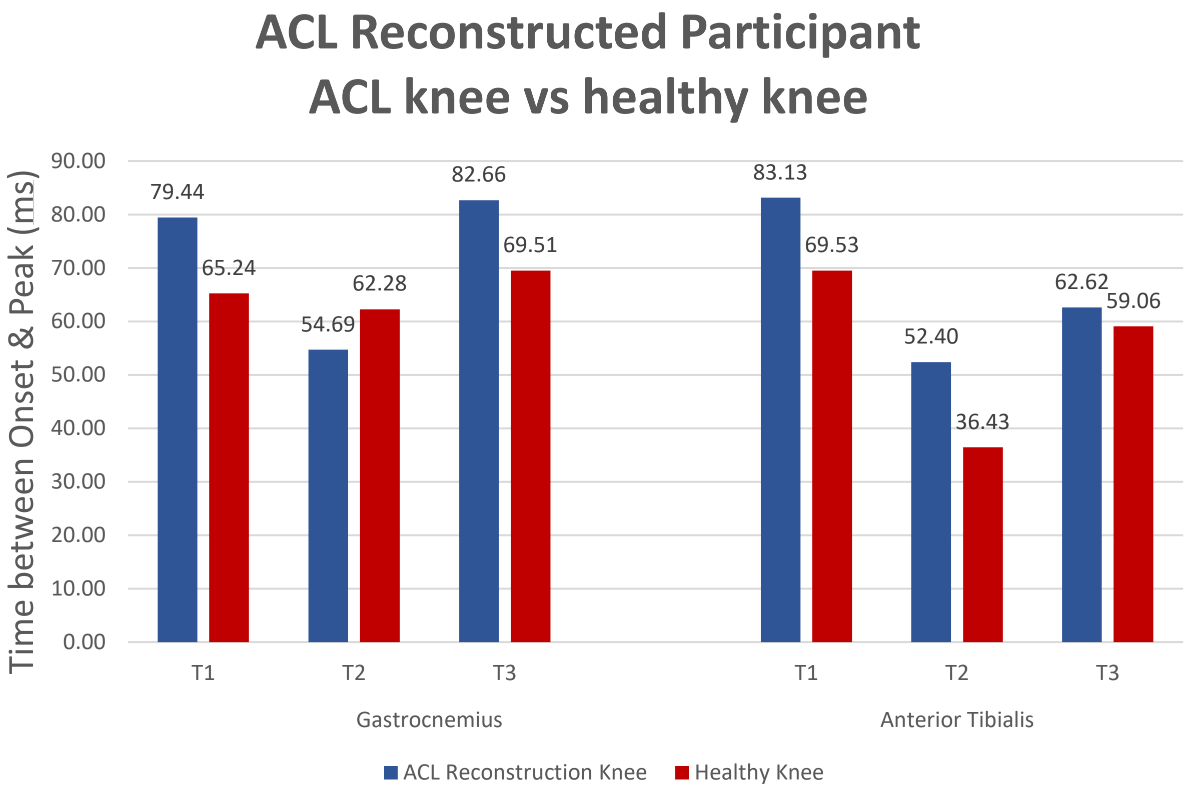


Figure 17. Repeated Measurements – ACL Reconstructed Participant

Even when examining the dominant (right) versus non-dominant (left) legs of all participants, Figure 18 compares the ACL participant versus all healthy controls. All of the participants were right leg dominant. The anterior tibialis shows both ACL and healthy participants have a slower dominant leg response but the ACL participant shows almost double the difference between the dominant and non-dominant leg. The gastrocnemius shows that healthy controls have a faster processing response on their dominant leg compared to their non-dominant leg, however for the ACL participant it shows the exact opposite, even though she is right leg dominant that leg has a much slower response compared to her healthy and non-dominant knee. From all of the healthy controls it is expected that the dominant leg would have a faster response time however since the ACL participant had surgery on the dominant leg the slower response is believed to be from proprioceptive deficiencies due to surgery.

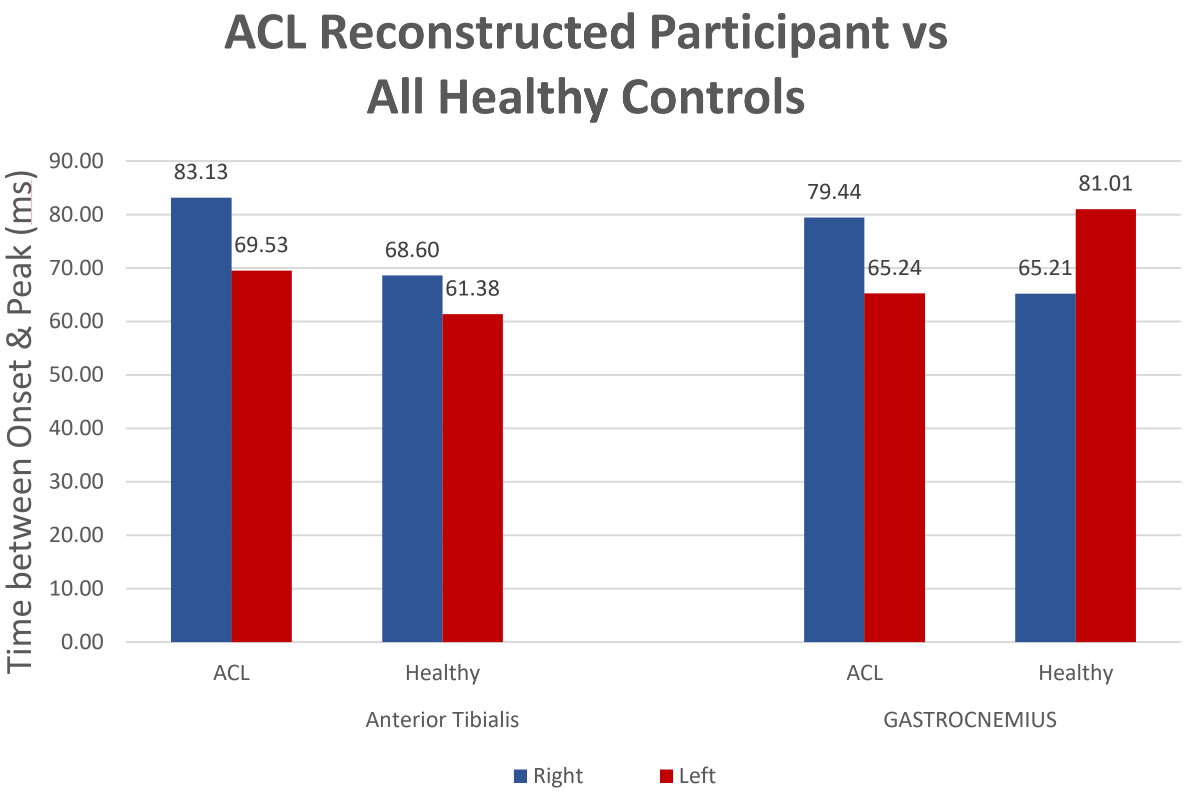


Figure 18. Dominant versus Non-Dominant Leg

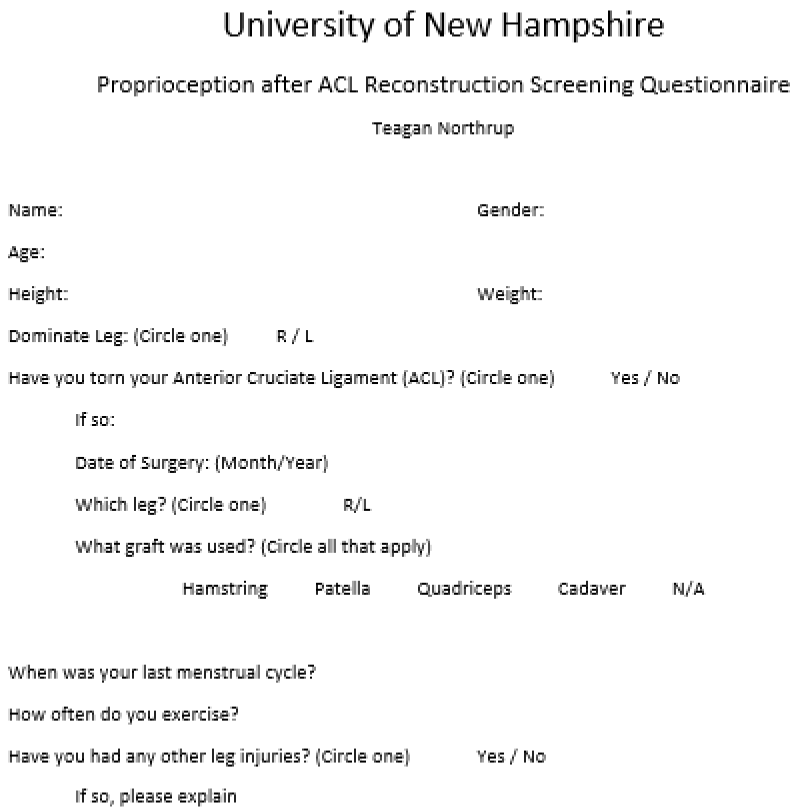
Conclusion

This study demonstrated a new method of measuring proprioception that allows the timing of responses to be examined using EMG and EEG signals. Using this method, proprioceptive deficits were found in the ACL reconstructed participant's knee compared to healthy controls as well as when compared to the ACL reconstructed participant's own healthy knee as a second control. However, since day to day activities can affect muscle fatigue and response, a single measurement may not be accurate and repeated measures may be necessary. Evidence exists that even with multiple measurements over time, responses within participants are not stable. Due to the low sample size of this project, future research should include more participants to test the statistical significance of the results. The study originally had more ACL reconstructed participants who had volunteered, unfortunately they could not participate because they suffered subsequent ACL injuries prior to testing. This challenge reflects the importance of this research – recurrence of ACL injuries are 60 times more likely than original injuries. The methods described in this report could be used to measure proprioception over the course of ACL rehabilitation to track improvements in recovery over time as well as to help determine whether participants are ready to return to activity.

References

1. American Academy of Orthopedic Surgeons, “Anterior Cruciate Ligament (ACL) Injuries”, Last Reviewed March 2014. [Online]. Available: http://orthoinfo.aaos.org/topic.cfm?topic=A00549. [Accessed: 15- March- 2018]
2. M. Solomonow, M. Krogsgaard, “Sensorimotor control of knee stability. A review”, *Scand J Med Sci Sports*, vol. 11, pp. 64-80, 2001
3. L. Y. Griffin, J. Agel, M. J. Albohm, E. A, Arendt, R. W. Dick, W. E. Garrett, J. G. Garrick, T. E. Hewett, L. Huston, M. L. Ireland, R. J. Johnson, W. B. Kibler, S. Lephart, J. L. Lewis, T. N. Lindenfeld, B. R. Mandelboum, P. Marchak, C. C. Teitz, E. M. Wojtys, “Noncontact Anterior Cruciate Ligament Injuries: Risk Factors and Prevention Strategies”, *Journal of the American Academy of Orthopaedic Surgeons*, vol. 8, pp. 141-150, 2000
4. R. V. West, C. D. Harner, “Graft Selection in Anterior Cruciate Ligament Reconstruction”, *Journal of the American Academy of Orthopaedic Surgeons*, vol. 13, pp. 197-207, 2005
5. N. Relph, L. Herrington, S. Tyson, “The effect of ACL injury on knee proprioception: a meta-analysis”, *Physiotherapy*, vol. 100, no. 3, pp. 187-195, Jul-Aug 2014
6. J. Baumeister, K. Reinecke, M. Weiss, “Changed cortical activity after anterior cruciate ligament reconstruction in a joint position paradigm: an EEG study”, *Scand J Med Sci Sports*, vol. 18, pp. 472-484, 2008
7. O. M. Knezevic, D. M. Mirkov, M. Kadija, A. Nedeljkovic, S. Jaric, “Asymmetries in explosive strength following anterior cruciate ligament reconstruction”, *Knee*, vol. 21, no. 6, pp. 1039-1045, Dec, 2014
8. M. S. Dhillon, K. Bali, S. Pranhakar, “Proprioception in anterior cruciate ligament deficient knees and its relevance in anterior cruciate ligament reconstruction”, *Indian J Orthop.*, vol. 45, no. 4, pp. 294-300, Jul-Aug, 2011
9. P. Godinho, E. Nioliche, V. Cossich, E. B. de Sousa, B. Velasque, J. I. Salles, “Déficit proptioceptivo em pacientes con reuptura total do ligamento cruzado anterior”, *Rev Bras Ortop*, vol. 49, pp. 613-618, 2014
10. D. R. Grooms, S. J. Page, J. A. Onate, “Brain Activation for Knee Movement Measured Days Before Second Anterior Cruciate Ligament Injury: Neuroimaging in Musculoskeletal Medicine”, *Journal of Athletic Training*, vol. 50, no. 10, pp. 1005-1010, 2015
11. M. Dhillon, K. Bali, S. Prabhakar, “Differences among mechanoreceptors in healthy and injured anterior cruciate ligaments and their clinical importance”, *Muscles, ligaments and Tendons Journal*, vol 2, no 1, pp. 38-43, 2012
12. L. Turner, “Development and Testing of a Balance Platform Perturbator for Research in Neuromuscular Physiology and Biomechanics”, *UNH Senior Project(ECE791/792)*, 2016
13. Ritter, Arthur B., Stanley Reisman, and Bozena B. Michniak. *Biomedical Engineering Principles.* Boca Raton: Taylor & Francis, 2005.
14. Mayo Clinic, “Electromyography (EMG)”, January 20, 2017. [Online]. Available: http://www.mayoclinic.org/tests-procedures/emg/basics/definition/prc-20014183. [Accessed: 29- April- 2017]

Appendix



University of New Hampshire

Proprioception after ACL Reconstruction Screening Questionnaire

Teagan Northrup

Name: Gender:

Age:

Height: Weight:

Dominate Leg: (Circle one) R / L

Have you torn your Anterior Cruciate Ligament (ACL)? (Circle one) Yes / No

If so:

Date of Surgery: (Month/Year)

Which leg? (Circle one) R/L

What graft was used? (Circle all that apply)

Hamstring Patella Quadriceps Cadaver N/A

When was your last menstrual cycle?

How often do you exercise?

Have you had any other leg injuries? (Circle one) Yes / No

If so, please explain