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# The Effects of Playing Surface and Prior Anterior Cruciate Ligament Rupture on Tibiofemoral Acceleration

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## ABSTRACT

Anterior Cruciate Ligament (ACL) injuries are one of the most common sports injuries amongst female athletes that result in an inability to play. Factors such as turf fields and a previous ACL tear increase the risk of ACL injury. Further risk is increased due to certain biomechanical and neuromuscular factors that females specifically possess. The purpose of this study was to identify the neuromuscular and biomechanical risk factors associated with ACL tears during a 120-degree cutting maneuver. Subjects included college aged (18-30) female athletes that currently participated in a sport that competes on turf fields. All levels were included (recreational, collegiate, intramural) as long as they currently participated. EMG was used to track muscle activation patterns and IMU was used to track tibiofemoral acceleration both inside the lab and outside on the turf field. The hypothesis was that there would be a difference in muscle activation as well as tibiofemoral acceleration between the affected leg (ACL reconstruction surgery leg) and unaffected leg. Furthermore, it was hypothesized that there would be increased quadricep to hamstring activation ratio as well as increased tibiofemoral acceleration between a turf and lab surface. Specifically, it was expected that the semimembranosus and biceps femoris would have a lower activation than the rectus femoris on both legs, but that the affected leg would see a higher quadricep to hamstring activation ratio than the unaffected leg. From this study, it was seen that there was a higher quadricep to hamstring activation ratio as well as higher femur to tibia acceleration between surfaces and limbs. It was concluded that a turf surface as well as previous ACL reconstruction surgery presents increased risk for possible ACL tears. The implications presented by this study include considering sport surfaces during rehabilitation and return-to-play guidelines as well as increase ACL injury preventions in exercises.

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# CHAPTER 1 - INTRODUCTION

## 1.1 GENERAL INTRODUCTION

Injury of the Anterior Cruciate Ligament (ACL) is one of the most common knee injuries seen in sports. In the NCAA Injury Surveillance Program (ISP), 1105 ACL ruptures were reported from 2004 to 2014 in the NCAA alone. Furthermore, of these 1105 reported ruptures, 126 of them were recurrent (Gans et. al., 2018). Most ACL injuries in sports are a result of non-contact mechanisms such as cutting. Several factors contribute to an ACL injury and tearing such as neuromuscular and biomechanical risks. The surface and prior ACL reconstruction surgery contribute to ACL ruptures as well.

It is known that women (compared to men) are at a higher risk for tearing their ACL due to neuromuscular and biomechanical differences. Changes of direction movements, specifically in sports where they are performed at a fast pace, have been shown to increase the risk of tearing the ACL due to the anterior shear force put onto the knee. Dos 'Santos et al. (2021) analyzed different cutting degree angles and concluded what impacts they have on biomechanics. Angles of greater degrees, between 90 and 180, have been shown to produce higher risk. Cuts made at high degree angles produce movement beyond what is considered normal for females, putting higher force anteriorly on the knee and increasing the possibility of having multiplanar knee joint loads (Fox et al., 2014, Donelon et al., 2020).

Biomechanical differences are analyzed using motion analysis and Inertial Measurement Units (IMUs) through three-dimensional kinematic analysis. Looking at hip, knee, and ankle joint angles during a cutting maneuver gives insight into the kinematic movement patterns and muscle force production of the body during the task. Looking specifically at the ACL during a cutting task, knee abduction moments and abnormal knee joint angles have been shown to be high-risk factors for ACL tears across all three planes (sagittal, frontal and transverse planes) (Beaulieu et al. 2009). Currently, motion analysis is considered the gold standard for kinematic analysis. However, a newer technology has been introduced to biomechanics for analyzing biomechanical risk factors. IMUs can give information such as the body's angular rate, orientation, and force. However, there is little information on IMUs in the biomechanics field, which leaves room for investigation on the usability and functionality of the technology in this setting.

Electromyography (EMG) shows the activation patterns of muscles during movement. When analyzing ACL injury risk factors, EMG gives input on the neuromuscular deficits. When comparing men and women muscle activation patterns during a cutting task, females exhibited decreased medial to lateral quadricep activation ratio (Myer et al., 2005, Besier et al, 2003). Furthermore, females have also exhibited high quadricep with low hamstring activation (Colby et al., 2000, Hanson et al., 2008). This deficit puts strain on the ACL due to the instability of the knee.

Another factor to consider, specifically when looking at a cutting maneuver common to sport movement, is the surface on which the athlete is playing. Natural grass and artificial turf have been shown to have both pros and cons. However, historically artificial turf has been shown to produce a higher rate of lower limb injury (Steffen et al., 2007). Furthermore, athletes transitioning between different surfaces for practice and playing require a high level of adaptivity. Not adapting quickly enough has been shown to result in more injuries as well (Kossin, 2018 and Steffen et al., 2007). Analyzing surface impact on muscle activation using EMG (Kossin, 2018) gives information on the adaptability needed by athletes as well as the risks on different surfaces.

Further risk can be seen in those with a previous ACL surgery. Having previous ACL surgery increases the risk of rupturing the same ACL again due to improper biomechanics and muscle deficits. Analyzing gait patterns is a simple way of identifying between-limb differences. When looking at previous ACL surgery differences, Sigward et al. (2016) used gait pattern as well as IMUs and ground reaction force plates. High levels of knee loading have been shown to increase the risk of an ACL tear. Structural instability and a lack of neuromuscular control on the surgery side also increase the risk of re-rupturing the ACL. These risks have been seen with jerk movements associated with the biomechanical deficits occurring during a cutting maneuver (Tedesco et al., 2020). King et al. (2018) analyzed biomechanics using ground contact time, total cutting time, and forward center of mass velocity to determine the differences in healthy and post-ACL surgery limbs.

### 1.2 Purpose of Study

The purpose of this study was to determine tibiofemoral acceleration using Inertial Measurement Unit (IMU) sensors during a cutting maneuver.

ACL injury risk factors (neuromuscular and biomechanical) were analyzed further using Electromyography (EMG) and motion analysis. Finally, assessment was done on different surfaces to analyze the difference in risk factors between surfaces.

### 1.3 Specific Aims

The specific aims of this study were,

1. To determine tibiofemoral acceleration using IMUs.
2. To analyze neuromuscular risk factors using EMG.
3. To analyze biomechanical risk factors using IMUs.
4. To assess surface impacts on muscle activation and body mechanics.
5. To analyze recurrent ACL surgery impacts on body mechanics and muscle activation.

### 1.4 Study Overview

ACL injury risk factors are analyzed using EMG and IMUs. The study includes two parts, one part done inside in the biomechanics laboratory and the second part is done outside on the artificial turf soccer field. In the first part, subjects are connected to EMG and IMU sensors in order to analyze biomechanical and neuromuscular risk factors. The second part is done outside on the turf field while connected to IMU and EMG only. This is done to compare the risk factors from the laboratory surface to the artificial turf surface.

Subjects include college aged females that play a sport on an artificial turf surface (includes soccer, lacrosse, and field hockey). Subjects are only included if they have a prior ACL reconstruction surgery on one side in order to compare between-limb differences from the healthy side (no prior ACL surgery) and the unhealthy side (prior ACL surgery).

A cut will be performed at approximately 135-degrees. This will be done 3 times to each side both inside the laboratory and outside on the turf field. The results will compare the healthy and unhealthy legs on both surfaces to identify biomechanical and neuromuscular deficits experienced after surgery as well as compare the surface impacts.

### 1.5 Thesis Structure

After Chapter 1, the Introduction, Chapter 2 contains a review of literature. Chapter 3 discusses the methods used to conduct the study. Chapter 4 contains the results and data collected. Chapter 5 includes the discussion and conclusion sections.

# CHAPTER 2 - LITERATURE REVIEW

## 2.1 OVERVIEW

This chapter is a review of the literature regarding anterior cruciate ligament (ACL) injuries. An anterior cruciate ligament (ACL) tear is one of the most common knee injuries, especially amongst athletes. There are several factors that contribute to this common occurrence such as biomechanical and neuromuscular risk factors, surface, gender, and sport-specific movements. Statistically, females are more likely to tear their ACL. Furthermore, those that play on artificial turf (sports such as soccer, field hockey, rugby, lacrosse) are placed at an even higher risk due to the injury causing capacity of the turf compared to natural grass. Analyzing biomechanical and neuromuscular risk factors has been done using electromyography (EMG) and motion analysis. However, inertial measurement units (IMUs) offer a new way of analyzing body kinematics in an on-field setting.

Section 2.2 discusses ACL statistics regarding injury occurrence. Section 2.3 and 2.4 review the use of EMG and motion analysis while discussing topics such as quadricep to hamstring muscle activation ratio (2.3.1) and muscle activation strategies during a cutting maneuver (2.3.2). Section 2.5 discusses IMUs and their validity and reliability in on-field testing use (2.5.2). Sections 2.6 reviews biomechanical risk factors such as change of direction movements (2.6.1) and joint kinematics (2.6.2). Surface impacts such as muscle activation differences (2.7.1) and injury risk (2.7.2) are discussed in section 2.7. The last section, 2.8 discusses ACL surgery impacts and how it affects hamstring muscles (2.8.2) and biomechanics (2.8.1).

## 2.2 ACL STATISTICS

Gans et al. (2018) analyzed primary and recurrent ACL rupture rates in 25 NCAA sports across all divisions from 2004 to 2014. Using the NCAA Injury Surveillance Program (ISP), they gathered data from the ACL rupture reports in 12 of the 25 sports analyzed. The purpose of this study was to assess the epidemiology of recurrent ACL rupture rates using the NCAA ISP as well as to compare the risk factors for recurrent rupture by sport, sex, event type (practice vs competition), and season (pre vs regular vs post). After a primary ACL rupture, 61-89% of athletes return to sports. Of these primary ACL ruptures, 1-11% rupture their ACL for a second time. In the study 1 in 9 primary ACL ruptures had a recurrent rupture in the ipsilateral knee. In women, recurrent ACL ruptures accounted for 14% of all ACL ruptures and in men, recurrent ACL ruptures counted for 10%. The most common risk for recurrent rupture of the ACL is through non-contact mechanisms, accounting for about 55% of all ACL recurrent ruptures. Without considering sex and sport, overall, those entering NCAA sports with prior ACL surgery have a significantly higher risk of re-rupturing their ACL at some point during their collegiate career than those who had no prior ACL surgery. During the time period of the study, there were 1105 reported ACL ruptures, 979 primary and 126 recurrent. There was a rupture rate of 32 for every 10,000 AEs (athlete-exposures). Of the 12 sports, the sports that saw the highest recurrent ACL rupture rates were men's football (41%), women's soccer (15%), and women's basketball (13%). The sports with the highest rates (per 10,000 AEs) of recurrent ruptures were men's football (15), women's gymnastics (8.2), and women's soccer (5.2). Looking specifically at the rates between Men's and Women's soccer, women were more likely than men to sustain recurrent ACL ruptures. The most common time for women to sustain a recurrent ACL rupture was reported to be during practice rather than during competition, however primary ACL rupture was higher during competition for both men and women.

## 2.3 ELECTROMYOGRAPHY

When analyzing ACL risk factors, EMG gives us an idea as to what muscles are firing and when they are firing during a cutting movement, which is a known facilitator of ACL tears. Studies have shown that specific firing patterns and muscle activation strategies could be a detriment to knee stability during cutting maneuvers. In women specifically, it has been shown that an important risk factor to consider is the quadricep to hamstring activation ratio. Colby et al. (2000) discusses quadricep to hamstring activation ratio. They stated that because of this high force production and activation of the quadricep muscle and the hamstrings being submaximal in activity comparatively, there is not sufficient support to prevent anterior tibial displacement (Colby et al., 2000). Myer et al. (2005) further explains muscle activation patterns in regard to knee stability by analyzing quadricep muscles.

### 2.3.1 QUADRICEP TO HAMSTRING ACTIVATION RATIO

Colby et al. (2000) discussed common movements for noncontact ACL injury across sports. They used 15 healthy collegiate and recreational athletes (both men and women) for their study with no prior ACL injury nor any prior knee injury or disease. EMG was used to assess four movements which included side-step cutting, cross-cutting, stopping, and landing. EMG activation was analyzed for the vastus lateralis and medialis, rectus femoris, biceps femoris, and the medial hamstrings (semimembranosus and semitendinosus) during the maneuvers. The study focused on the subject's dominant side (test leg) when placing the electrodes on muscles. For the sidestep cutting, subjects ran at a self-selected 75% speed and changed direction at a 45° angle using the non-test leg as the first step when changing direction. The results showed that for this maneuver there was a significant increase in quadricep activation and a slight decrease in hamstring activation directly after foot strike. For the cross-cutting maneuver, the subjects ran at 75% speed again, but this time they put the plant foot on the ipsilateral side and moved the other leg across the plant leg heading towards the new direction. The results of this portion were similar to the sidestep cutting results with the quadriceps increasing in activation and hamstrings only slightly increasing after foot strike. Stopping was analyzed by having the subject run at 75% speed with deceleration and stopping with the test leg. The results again showed the same effect as the sidestep and cross-cutting maneuver. When analyzing a landing movement, the subjects landed on both legs from a box 0.4m in height and then pivoted immediately to the opposite side of test leg. The hamstrings were shown to have moments of increasing and moments of decreasing activation after foot strike, while the quadriceps showed an immediate increase with a decrease in the few seconds after peak contraction.

Hanson et al. (2008) hypothesized that when compared to male soccer athletes, females would exhibit greater quadriceps activation alongside lesser hamstring, gluteus medius, and gluteus maximus activation during a side-step cutting maneuver. Furthermore, they also expected to see increased quadricep to hamstring coactivation ratios during the same maneuver. Participants had no history of ACL injury nor any serious lower limb injury within the past month that required them to miss 3 consecutive days of practice. Surface EMG was used to record muscle activity of the rectus femoris, vastus lateralis, semitendinosus, semimembranosus, biceps femoris, gluteus medius, and gluteus maximus. A force plate was used to identify ground contact and stance phase. Motion analysis was used to measure horizontal movement velocity during the maneuver. Only the dominant leg was tested which was defined as the leg used to kick a soccer ball to maximum distance. The cutting maneuvers consisted of doing a side-step cut with a 3.04m run up and a box jump landing into a side-step cut. The subjects would make the cut to the opposite side of the dominant leg. The results of this study showed that females exhibited much greater vastus lateralis activation during both the preparatory phase and the loading phase of the cut. The gluteus medius showed no difference in activation between genders during the loading phase but did for the preparatory phase where females showed higher activation. The rectus femoris, semimembranosus, semitendinosus, biceps femoris, and gluteus maximus showed no significant differences in activation between genders. However, overall females showed greater quadricep to hamstring coactivation.

### 2.3.2 Muscle Activation Strategies during Cutting Maneuvers

Myer et al. (2005) analyzed the differences in muscle activation strategies between genders while participants performed a high ACL injury risk maneuver. It was hypothesized that females would have a higher lateral quadriceps activation compared to males. The participants included in the study had to be physically active at least once a week and could not have a history of knee injury or surgery. There were 10 adult males and 10 adult females who participated in the study in order to identify gender differences. EMG was attached to the vastus lateralis, vastus medialis, as well as the anterior tibialis to analyze the muscle activation patterns of these muscles. A side-step movement was performed with the subject starting from a standing position with the feet wider than shoulder width apart. The subject would then lean to the right until the knee was at 30-degrees of flexion and return to knee straight. From the results, it was concluded that the decreased medial to lateral quadricep ratio could be due to a decreased control in the coronal plane at the knee. This result could also increase the anterior shear force by compressing the lateral joint. From this activation pattern, there is an increased risk for ACL injury due to increased knee valgus from the forces experienced at the knee.

Besier et al. (2003) investigated the muscle activation patterns of the muscles surrounding the knee during pre-planned as well as unplanned cutting tasks. The researchers hypothesized that average muscle activation will increase during the cutting tasks compared to a straight run, muscle activation of the medial and external rotation muscles will increase in the pre-planned sidestepping task compared to the straight run, and activation of lateral and internal rotation muscles will increase during the pre-planned cross-over cut compared to the straight run. They also included unplanned cutting tasks in their study in which they hypothesized that the Central Nervous System (CNS) will adopt a generalized co-contraction strategy rather than a direct activation strategy as well as an overall greater average muscle activation compared to the pre-planned cutting tasks.

The subjects included in this study were all healthy male soccer players, aged 18 to 25 with no history of lower limb injuries. They completed four tasks including a straight run, sidesteps at 30-degrees and 60-degrees, and a 30-degree cross-over cut. To eliminate the effect that shoes can have on muscle activation, participants were barefoot during testing. EMG was used to analyze muscle activation patterns during predetermined maneuvers. With the EMG, a force plate and motion analysis were also used to gather data on kinematics, kinetics, and ground reaction force.

During the preplanned conditions, muscle activation overall was higher than during the run task. Specifically, the valgus/varus and internal/external loads were significantly greater during the cutting tasks compared to the run task. Furthermore, during the preplanned cutting tasks, the medial muscle group was higher in activation at pre-contact compared to the lateral muscle group. For the 60-degree angle, there was a 33% increase of the medial muscle group and for the 30-degree angle, there was a 22% increase in activation in the medial muscle group. In the run task, there was no difference in activation between the medial and lateral muscle groups. The biceps femoris/ semimembranosus activation ratio varied throughout the different tasks. Overall, the 60-degree cut showed the highest activation ratio (with the semimembranosus being activated more than the biceps femoris), followed by the 30-degree cut, the run, and then the crossover task. In the unplanned conditions, the net average muscle activation increased 10-25% for the cutting tasks. However, there was no significant difference in the co-contraction ratio (CCR) between the planned and unplanned cutting task, indicating that the flexor/extensor muscle ratio remained unchanged. Furthermore, there was also no significant difference between the medial and lateral muscle groups activation during any of the tasks at all phases.

The run task saw no significant difference in activation and the cross-over task only saw a slight difference during the weight acceptance phase. In conclusion, the hypothesis that the CNS activates knee muscles to stabilize the knee for varus/valgus and internal/external rotation was proven. During the cutting tasks the study showed increased muscle activation compared to the run task, which can be an indicator of knee stabilizing factors. There was also higher activation during the pre-planned cutting tasks in the pre-contact phase, indicating that anticipation is a factor in muscle activation. On the other hand, there was higher activation for the unplanned cutting task in the weight acceptance phase, further providing evidence that anticipating the maneuver influences muscle activation patterns. For the other hypothesis, it was found in the study that there is a combination of co-contraction and selected muscle activation throughout the different tasks in order to best accommodate the extraneous movements for injury prevention. For example, medial muscle groups were recruited more to counter the external valgus load during the cutting task as well as the biceps femoris being recruited more to counter the internal rotation moments. The third hypothesis made by the researchers was not supported by the study. The cross-over task did not show a significant difference in the biceps femoris/semimembranosus activation ratio as well as the medial/lateral muscle group activation ratio to stabilize the knee for this movement. A possible explanation for the lack of difference observed could be the amount of familiarity for athletes with this movement because it is not as common as the run or cutting task, which could lead to a less fine-tuned pre-programmed muscle activation pattern.

### 2.4 Motion Analysis

Understanding kinematics and kinetics in relation to knee, ankle, or hip joint angles provides data on the body's movement patterns that may be a source of ACL injury. Motion analysis utilizes a multi-camera setup to analyze biomechanics in a three-dimensional perspective. When investigating a cutting maneuver as an ACL risk factor, Beaulieu et al. analyzed knee angles in relation to muscle force production in section 2.4.1.

Beaulieu et al. (2009) analyzed the amplitude and timing of muscle recruitment of lower limbs as well as three-dimensional kinematics during an unanticipated cutting maneuver. Fifteen men and fifteen women elite soccer players were used in this study to observe the difference between genders. All players had at least seven years of experience and were right leg dominant. To be included, the subject had to have no prior knee injury or any serious prior lower limb injury as well as no current lower limb injury. EMG was used to record muscle activity during movement. EMG was connected to the vastus lateralis and medialis, rectus femoris, biceps femoris, semitendinosus, medial and lateral gastrocnemius, and the tibialis anterior. Reflective markers and a motion analysis system (seven cameras) were used to collect and analyze the kinematic data. Joint angles were obtained for the hip, knee, and ankle in the sagittal, frontal, and transverse planes. A force platform was used to determine the stance phase of the cutting maneuver based off the heel strike and toe-off timing of events. Each participant performed 5 cutting trials. For a successful trial, they had to approach the force platform at 4-5 m/s, step on the platform with their right foot and change direction (cut) to the opposite side (left) at a 45-degree angle from the line of the initial run up to the platform. To evaluate the unanticipated aspect, the study utilized an illuminated target board that was triggered 2 meters before the cutting point. The target board had three color options (orange, green, and red) that represented the movement that was to be done by the subject. Analysis was done from the data collected during the cutting phase. The cutting phase was defined as the time from maximum knee flexion angle of the right knee to right toe off. The muscle activation results of the study showed no gender differences in timing and amplitude for the vastus lateralis and medialis, the biceps femoris, or the medial gastrocnemius. However, for females, the semitendinosus activated much sooner, and they had higher peak activity for the rectus femoris when compared to males. Females also had higher tibialis anterior activity at initial contact and had greater lateral gastrocnemius activity when performing the task. The kinematic results of the study showed similar hip kinematics; however, females had decreased hip internal rotation at initial contact and decreased peak hip internal rotation. Similar knee joint kinematics were observed in the sagittal and transverse planes. Females showed greater knee abduction angles during the cutting task. Furthermore, greater ankle pronation was observed in women at initial contact, and they had greater peak ankle pronation compared to males. To start, activation of the lateral gastrocnemius could be a major cause of knee abduction moments (KAMs) which is a facilitator of ACL tears. Furthermore, this activation demonstrates an imbalance in medial and lateral muscle activation further causing more knee abduction at foot strike. It was also found that there was an imbalance in activation between the vastus lateralis and vastus medialis. The vastus lateralis was found to be activated to a much higher extent than the vastus medialis, which can also be a cause of knee abduction moments. From this study, it can be concluded that an overall imbalance of medial to lateral muscle activation is a probable cause of KAMs. KAMs put the ACL at risk for injury especially at initial contact when knee position is crucial for leg stability. It is possible that the rectus femoris had high activation to combat this instability. When compared to males, females had higher rectus femoris activation, which could be due to the difference in knee position during initial contact.

### 2.5 Inertial Measurement Units

Inertial measurement units (IMUs) are a relatively new technology to use for biomechanical analysis. IMUs use accelerometers, gyroscopes, and sometimes magnetometers to gather data on the body's angular rate, orientation, and force. Weygers et al. (2020) stated that IMU sensors are becoming increasingly popular in clinical practices. While motion capture systems are currently the gold standard for assessing body kinematics, IMU sensors allow for more versatility and functionality due to the ability to use them in other locations besides in the laboratory. Section 2.5.1 explains the correct placement of IMU sensors in order to get the most accurate data. Furthermore, section 2.5.2 discusses the validity and reliability of IMU sensors since they are a newer technology in the biomechanics field.

#### 2.5.1 IMU Sensor Placement

Weygers et al. (2020) reviewed existing literature for the methodological requirements when using IMU sensors to assess lower limb joint kinematics. To be included in this review, the study being evaluated had to include a reference system to compare the IMU sensor system to. Furthermore, studies that did not mention the methodologic applicability of IMU sensors in a setting outside of the lab were excluded. A total of 31 articles were included in this review and were analyzed for study characteristics (such as participant information, activity assessed, and joints of interest), signal processing characteristics, and study results. The sensors typically followed a pattern of placement at adjacent segments about the joint of interest. Furthermore, sensor placement considered the joint center, sensor to segment alignment, and sensor orientation. While this review provided a basic explanation of the methodology of IMU sensors, further research with the technology could be more specific. The review mentioned looking at more complex joint motions. While the knee is classified as a hinge joint, there are still possibilities for other planes of motion to be involved during more complex human movements, such as in landing and cutting which are often seen in sports.

#### 2.5.2 IMU Validity and Reliability

Alanen et al. (2021) reviewed the existing data on using IMU sensors to analyze change of direction movements. The other goal of this study was to determine the validity and reliability of IMU sensors for analyzing change of direction movements through a review of the literature. Forty-nine studies were selected for the final review after meeting certain criteria outlined by the researchers. The participants in the studies included generally ranged from 18 to 42 years old, except for three of the studies where participants were under 18, one with both youth and adults, and ten that did not report the ages of the participants. Multiple ground surfaces were used across the studies. Thirteen of them were strictly conducted in the laboratory and seventeen of them were conducted in indoor sports facilities such as basketball courts, dance halls, etc. Nine studies were conducted on outdoor sports fields and two included both indoor and outdoor settings. Eight of the studies did not mention study settings. In thirty-three of the studies, participants performed anticipated change of direction maneuvers. Two of the studies used both anticipated and unanticipated change of direction, however none analyzed just unanticipated change of direction movements. Eight of the studies analyzed the change of direction movements in a practice or game setting so that it was as realistic as possible for both planned and unplanned movement. Furthermore, multiple angles were used for the change of direction movement throughout the studies. Many of them used a combination of 45-degree, 90-degree, 135-degree, and 180-degree angles. Of the forty-nine studies, eleven of them evaluated the validity and reliability of IMU sensors. Eight of these studies compared IMUs to a gold standard to measure concurrent validity, and three of the studies focused on the construct validity of the sensors. For the concurrent validity studies, IMUs were compared to motion capture systems, force plates, and high-speed cameras. Validity was proven in the three studies that looked at peak acceleration, average loading rate, and impulse. From these studies, it was concluded that IMU estimates can provide accurate information regarding the vertical component and magnitude of step-average ground reaction force during a 45-degree change of direction movement. Also, during these studies, the IMU sensors produced acceptable measurements for peak foot strike impact forces for both 45 and 90-degree change of direction. Furthermore, validity was proven in two more reviews that looked at magnitude of inertial movement and heading angle compared to high-speed video. IMUs produced acceptable measurements for change of direction angles and with the use of an accelerometer, gyroscope, and magnetometer, different actions such as high acceleration and deceleration, were able to be accurately analyzed by IMUs. Three of the studies used construct validity to evaluate IMU sensors.

Each study used their own metric of evaluation with different tools to derive these metrics. Rate of change in acceleration, average instantaneous net force, and transitional angular displacement of segment along with symmetry index were used for analysis. The results concluded from these studies showed that IMUs produced acceptable measures when looking at variations between tasks and between participants, average force produced compared to overground speed, and joint stability after rehabilitation during change of direction movements. Since most of these tests were done in a controlled laboratory setting, they concluded that the results cannot be generalizable to on-field activity. More research should be done on sport playing surfaces to increase the generalizability of the IMU results. Furthermore, the imbalance of male to female participant ratio could have some effect on the outcome of the studies. It is known that females experience less knee and trunk stability as well as multiple lower limb deficits during change of direction movements. It would have been beneficial for the review to evaluate more articles including females. If this was not possible, it could be an indicator that more studies need to be done with female specific subjects because this population is more likely to show discrepancies in measurements which would allow for a better comparison of IMUs to gold standard technologies.

## 2.6 Biomechanical Risk Factors

Change of direction (COD) movements, as discussed in section 2.6.1, are a common non-contact ACL injury mechanism. The ACL is loaded and strained during these movements because of knee flexion, rotation, and abduction moments during extended knee postures. Furthermore, biomechanical deficits such as knee valgus and hip internal rotation increase the potential for ACL rupture. In section 2.6.2 Fox et al. (2014) looked at the ranges of hip and knee joint kinematics for women during different sport-related movements and going beyond these normal ranges adds an even greater risk of injury.

### 2.6.1 Change of Direction Movements

Dos 'Santos et al. (2021) hypothesized that during sharper COD movements there would be greater breaking forces, knee abduction angles, multiplanar knee joint moments, longer ground reaction contact times, lower velocity profiles, greater lower-limb flexion in the sagittal plane, greater pelvis rotation, and greater initial foot progression angles. The participants in this study included twenty-seven adult men (18+) from multiple sports. All athletes had to have competed in their respective sport at the semi-professional level for at least five years. To be included, the athlete had to be free from current injury and have no prior traumatic knee injury. Motion analysis and GRF data were used to analyze the kinematic and kinetic data. A total of six trials for each direction was performed by the participant. The change of direction task was performed at 45-degrees, 90-degrees, as well as 180-degrees. Participants were instructed to complete the movement as fast as possible to mimic a game-like situation. The results of the study showed that as change of direction angle increased, performance variables such as exit velocity, final foot contact (FFC), and approach all decreased. On the other hand, as direction angle increased, ground contact times (GCT) increased as well. Furthermore, greater peak knee abduction angles (KAA) were observed only in the COD at 90-degrees, however initial contact KAAs were greater in the COD at 45-degrees and 180-degrees. Vertical ground reaction force (VGRF) decreased as COD angles increased. During COD at 45-degrees, greater peak hip, knee, and ankle dorsi-flexion moments were observed compared to the COD at 90-degrees and 180-degrees. In the sagittal plane, greater peak hip and knee flexion angles were observed for the COD at 180-degrees compared to the other angles. Greater initial angles for the hip, knee, and ankle dorsi-flexion were observed during the 45-degree COD compared to the 180 and 90-degree angles. Pelvis rotation increased as COD angles increased. Lateral trunk flexion angles were lower during the 180-degree COD compared to the other COD angles.

### 2.6.2 Joint Kinematics

Fox et al. (2014) did a systematic review of studies that looked at lower limb kinematics of females during drop vertical jumps, drop landings, and side-step cutting tasks. They wanted to determine what were considered normal ranges for hip and knee joint kinematics during these tasks. Articles were included if the female subjects were 16 years of age or above and did not have any history of lower back or lower limb joint injury. The subjects had a variety of sport participation, ranging from non-athlete to athlete (or combination or general), as well as different activity levels from recreational and high school to professional. The first task assessed was the single leg drop landing. Drop landing heights varied among the articles including heights of 20 centimeters (cm), 30 cm, 60 cm, and the subjects maximum vertical jump height. The second task was the double-leg drop vertical jump. Drop heights included 30 cm, 31 cm, 45 cm, 50 cm, and 60 cm. The third task was the side-step cut. Cuts were made at 45 degrees, 35 to 55 degrees, and 60 degrees. Approach speed to the cut was also included with speeds being 3 m/s, 4 to 5 m/s, 4.5 to 5 m/s, a mean speed of 4.85 m/s, and one with the subject's fastest speed possible. When assessing frontal plane kinematics for these movements, valgus alignment was concluded to be a primary risk factor for ACL tears. During the double-leg vertical jump landing, it was found that subjects who sustained an ACL injury landed with anywhere between –5 and –9 degrees for valgus alignment. Normal angles for those who did not sustain an ACL injury had valgus alignment angles of –1.4 to 3.4 degrees. Frontal plane kinematics at the hip are also a known factor for ACL risk. Increased hip adduction could result in the medial collapse of the knee which increases knee valgus, therefore increasing the risk of ACL tear. It was concluded that in many cases that resulted in an ACL tear, hip adduction angles were greater than 5 degrees. Looking at sagittal plane kinematics, hip and knee flexion values increased from initial contact to peak for all tasks except cutting. Jump landing tasks (both single and double) have shown high probability of ACL strain when knee flexion angles are lower at landing. Contrary to popular belief, it is typical of females to have hip and knee angles fall within normal range, regarding the sagittal plane, during ACL injury, which demonstrates the increased risk of ACL tear that females have just from their normal kinematics in the sagittal plane. In transverse plane kinematics, internal rotation of the knee produced higher ACL strain compared to external rotation. External rotation of the hip produced a higher risk for ACL injury during the double-leg vertical drop jump. On the other hand, hip internal rotation produced higher risk during the side-step cutting task. In conclusion, it can be assumed that higher ACL injury risk comes from abnormal movements during the athletic tasks analyzed. All planes showed a significant increase in ACL injury risk when angles and rotations were outside of "normal" range except for hip and knee angles in the sagittal plane. Due to a lack of data, "normal" ranges could not be provided for single leg and double leg drop vertical jumps.

Donelon et al. (2020) analyzed different cutting maneuvers and the different effects it had on the ACL in terms of loading and ground reaction force. Cutting motions in sports increases the possibility of having multiplanar knee joint loads (KJLs), which increases the capacity of ACL loading and strain. In general, greater angled cuts resulted in greater GRF therefore increasing ACL injury risk. At the trunk, contralateral trunk lean is a big issue for female athletes, and many with ACL injuries were recorded having contralateral trunk lean during the incident. In a contralateral trunk lean, there is a greater perpendicular distance between the GRF and the knee, which increases KJLs due to the trunk leaning in the opposite direction of travel. Particularly in ball carrying sports, it is highly likely that there is contralateral trunk flexion and possible trunk rotation because it helps with 'faking out' the opponent. Hip flexion and excessive hip abduction were determinants of KAM which increase the risk of ACL injury. In this situation, the knee is placed in a more medial position in the GRF vector. This position increases the perpendicular distance of the moment arm which leads to greater KAM. A study assessed in this article determined that a 45-degree cutting angle and an internally rotated hip produced a greater KJL. Moving down to the knee, knee abduction angle in terms of frontal plane knee motion has been shown to be a determinant of KJLs. Motions such as internal knee extension, knee internal rotation, and knee flexion elicit greater KAMs. At the ankle, the article assessed sagittal plane alignment, foot strike patterns, and foot progression angles to have put strain on the ACL. Sagittal plane alignment increases KAM when landing in a downward angled position at the ankle. When looking at foot strike patterns between a rear foot strike and a forefoot strike, a forefoot strike results in a lower GRF and lower power absorption at the knee whereas a rear foot strike generates a greater KAM. The foot progression angle also influences ACL loading. An inverted foot angle causes tibial internal rotation, and an everted foot angle causes eversion and pronation. The main ACL stressors, as determined by the article, were external knee flexion, internal rotation, knee at full extension, greater tibial angular acceleration, and deceleration while applying greater antero-posterior braking forces in the steps prior to the actual turn.

## 2.7 Surface Impacts

In general, adaptations are required when playing sports on multiple surfaces. Steffen et al. (2007) concluded (section 2.7.2), that switching between surfaces causes more injuries due to a lack of quick adaptation. However, when looking at injury rates, artificial turf has been shown to have the highest rate amongst all surfaces including natural grass and a hard floor or court. Kossin (2018) concluded, uneven surfaces (artificial turf and natural grass) are associated with more knee and ankle instability (section 2.7.1).

### 2.7.1 Muscle Activation Differences Between Surfaces

Kossin (2018) analyzed the differences in functional tasks on different surfaces such as turf, natural grass, and in a laboratory setting. The study looked at muscle activation and plantar pressure of lower extremities to compare the functional tasks. Surface EMG was used to collect muscle activation data of the gluteus maximus, gluteus medius, biceps femoris, vastus lateralis, vastus medialis, gastrocnemius (lateral head), peroneus longus, and the anterior tibialis. IMU sensors were placed on the pelvis, mid shank, and mid-thigh to analyze kinematics. In-shoe sensors were used to collect plantar pressure data during the tasks as well. Participants had to be free of any lower extremity or lower back injury within the prior six months and no lower extremity surgery history. All participants wore standardized shoes to control confounding factors with shoe-surface interaction. Three functional tasks were predetermined for the participant, which included a 10-yard jog at 50% speed, 10-yard sprint at 100% speed, and a 10-yard jog at 50% speed with a cut off the dominant leg. Each task was performed three times on each of the three surfaces (turf, natural grass, and the lab). The results of the study showed that the gluteus medius had higher activation in the laboratory setting compared to the turf during the jogging task. The peroneus longus had significantly higher activation on the turf compared to the natural grass during the jogging task, however during the cutting task, it had higher activation on the natural grass. The biceps femoris showed higher activation on the turf than the natural grass during the sprinting task. As for the plantar pressure, no significant difference was found for mean plantar pressure for the tasks across the three surfaces. However, there was a difference for pressure time integral during the cutting task, with higher KPa per second on the turf compared to the natural grass. The gluteus medius had higher activation in the laboratory setting, which could be due to the familiarization of ground surface found to alter body mechanics. Since the football players are more used to being on the grass and turf, they could have adopted an altered body mechanic in order to compensate for the unfamiliar surface in the laboratory when performing these movements. The difference in activation of the peroneus longus could be explained by the differences in contact that the foot has with the ground between the surfaces. It has been shown that on uneven surfaces (such as turf and grass) there is higher activation in lower limb muscles during complex tasks to accommodate for more ankle and knee stability.

### 2.7.2 Injury Risk on Artificial Turf

Steffen et al. (2007) examined the injury risk on artificial turf compared to natural grass. Teams from a European youth soccer league were put into one of two groups. One group was the intervention group who received a training program specifically to prevent injuries while the second group trained as usual. Each team's coach was asked to document specifics of the injury such as playing surface (artificial turf, natural grass, gravel, or indoor floor). Teams were also assigned a physical therapist to further monitor injuries. Upon injury, athletes were interviewed by the study team via a questionnaire to assess injury aspects. Injury aspects included contact vs. non-contact mechanisms, injury type, and injury location. Injuries were then classified into 3 categories based on how long it took for the player to return to training. Minor severity included return to play under 7 days, moderate was 8-21 days, and major was anything over 21 days. Of the 526 injuries recorded, 456 were acute injuries (such as sprains and strains) and 70 were overuse injuries. For acute injuries, the incidence rate was 7.5 times higher during games than practice settings. Forty-two percent of acute injuries were due to non-contact mechanisms and 58% were due to contact mechanisms, with the most common being ankle sprains. The most common overuse injuries included anterior lower leg pain (36% of all overuse injuries) and knee pain (21%). During match settings, a significantly higher rate (almost double) of injury was experienced on artificial turf for major injuries than on natural grass. On the other hand, minor injuries had a lower injury rate on artificial turf compared to natural grass. More ankle and knee ligament injuries were recorded for artificial turf than natural grass. Of the ACL injuries, 3 occurred on grass, 2 indoor, 2 on gravel, and 4 on turf. Of these 11 ACL injuries, 10 occurred in matches, 4 from contact and 6 from non-contact mechanisms. Overuse injuries were hard to track in this study since they have a gradual onset, so it was hard to find the specific details about the injury such as mechanism or surface type. However, it has been postulated that switching between different surfaces could cause an increased risk of overuse injury due to the players' lack of quick adaptation.

### 2.8 ACL SURGERY IMPACTS

Coming back to a sport after having ACL reconstruction surgery has many challenges mentally and physically. Biomechanical deficits and asymmetries exist as proven by Tedesco et al. (2020) and King et al (2018) (section 2.8.1). Furthermore, while women already have a large difference in hamstring to quadricep muscle activation ratio, Messer et al. (2018) described the deficits experienced after an ACL reconstruction surgery in regard to the hamstring muscles (section 2.8.2).

#### 2.8.1 BIOMECHANICAL DIFFERENCES

Tedesco et al. (2020) aimed to focus on the after-effects of ACL damage in rugby players by analyzing change of direction movements in healthy and reconstructed ACLs. This study also aimed to distinguish between healthy and post-ACL reconstruction groups by using IMU sensors and data driven machine learning models. The ACL surgery had to have taken place five to ten years before data collection, had to have returned to a competitive level of play, and be cleared by their clinician for return to play. All post-ACL surgery subjects had ACL surgery on their left leg, and one had a recurrent ACL injury, both on the left leg. Subjects were asked to complete a five-meter run, make a 45-degree cut to the side indicated during the initial five-meter run, and then continue for another three meters after the cut and stop. The IMU sensors were attached to the subjects' anterior tibia (10 cm below tibial tuberosity) and the lateral thigh (15 cm above tibial tuberosity). From the IMU sensors, they were able to measure the 3D angular rate, the magnitude of the 3D acceleration, the 3D jerk signal, and the 3D acceleration in the body frame and gravity frame. The results of this study showed there is a significant difference between the unaffected (healthy ACL) and affected (post-ACL surgery) legs for gait cycle time and cadence. The study concluded that the observed variables of interest following statistical analysis showed that there was a significant difference between ACL reconstructed knees and healthy knees. It was found that many of the chosen movements that produce ACL injuries are related to sagittal plane movements, therefore suggesting alterations in movement in this plane. It has been confirmed that the jerk movements observed in the sagittal plane are an indicator of structural instability and a lack of neuromuscular control, particularly in those individuals with ACL reconstructed knees. It was unknown in this study if the participants with ACL surgery had experienced leg asymmetries prior to the surgery, therefore leaving open the question whether the asymmetries experienced post-surgery were truly due to ACL reconstruction.

King et al (2018) assessed biomechanical differences during a change of direction movement between those who have had an ACLR and those who haven't. There were two parts to this study to assess the differences. The first part analyzed timing differences and biomechanical variables between those with the surgery and those without the surgery. The second part consisted of identifying the differences in kinematics and kinetics between the two groups. Subjects included male athletes (between the ages of 18 and 35) that participated in multidirectional field sports (I.e., soccer, rugby, hurling, and Gaelic football). The subjects, on average, were 8.8 months out from primary ACLR surgery and did not have any other surgical repairs. Testing was done in a biomechanics lab using an eight-camera motion analysis system and two force platforms. An AstroTurf surface was used to mimic on-field movement. The change of direction movement consisted of performing a 90-degree cutting maneuver with a 5-meter run to start. The subject completed 2 submaximal and 3 maximal speed trials on each leg. Speed gates were used to assess the time performance for each trial with timing starting 2 meters from the start line and 2 meters to either side after the cut. To do the unplanned trials, the subject started at the line and broke what they called the "trigger gate" which was 2 meters after the start line. After hitting the trigger gate, the gate either to the left or right opened, signaling the subject to cut in that direction. Ground contact time, total cutting time, and forward center of mass (COM) velocity at initial contact were used to analyze between-limb differences. The results of this study showed no significant difference in completion time as well as ground contact times for both the planned and unplanned cut in those with and without an ACLR. The ACLR limb however did show a significantly slower COM velocity at initial contact. There were several biomechanical differences observed between the two groups. The biggest difference observed was less internal knee valgus moments in the ACLR limb in the middle for the stance phase compared to the side without the ACLR. The ACLR sides also saw a smaller knee flexion angle, less ankle external rotation, less knee external rotation, less knee extension, and less knee internal rotation angle in the stance phase. Other biomechanical differences included the pelvis being less rotated towards the direction of travel in the stance phase during the unplanned change of direction movement as well as greater hip abduction and a lower posterior ground reaction force.

Sigward et al. (2016) analyzed gait patterns in subjects 3 months post ACLR surgery. This study used Inertial Measurement Units (IMUs) to analyze the differences in gait between limbs. Participants had to be 8 to 16 weeks after surgery. No concurrent knee injury nor a current injury to the contralateral limb that would influence gait could be present to be included in this study.

IMU sensors were attached to the lateral shanks bilaterally with the x-axis of the sensor aligning with the lateral epicondyle and the lateral malleoli. In addition to IMU sensors, they also used force plates to collect ground reaction force data and a motion capture system (11 and 14 camera) to analyze kinematic data. A trial consisted of the subject walking (at their own pace, known as self-selected velocity) for ten meters. To complete a successful trial, the participants had to make full contact with the force plate and their gait velocity had to fall within 5% of their self-selected velocity. The results of this study showed that there was no timing difference in stance and swing phases of gait between limbs. Furthermore, the study showed that even though there are no observable deviations in gait 8-12 post-surgery, there are still significant asymmetrical differences in knee loading mechanics. Peak shank angular velocity and peak knee extensor moments were significantly smaller in the surgical knee during loading response. Overall, this study showed that even though there are no observable gait deviations 8 to 12 weeks post-surgery, there are still biomechanical deviations that need to be considered. It also proved that IMU sensors are a useful tool for analyzing biomechanical deviations.

### 2.8.2 Hamstring Muscle Deficits

Messer et al. (2018) analyzed hamstring activation patterns in individuals with an ACL reconstruction, specifically those with a semitendinosus autograft. It was hypothesized that the limbs with a previous ACLR would show deficits in semitendinosus activation compared to the contralateral side. It was also hypothesized that there would be smaller semitendinosus volumes and smaller anatomical cross-sectional areas (ACSA) and lengths as well as lower eccentric knee flexor strength. All participants were at least 12 months and up to 78 months post-op. Participants underwent rehabilitation for their injury and were cleared for their pre-injury levels of training and competition. Participants did the Nordic eccentric hamstring exercise (Nordic hamstring curls) for five sets with ten repetitions and a one-minute rest in between. Ultrasound imaging and MRI were used to identify hamstring muscle length, muscle volume, and anatomical cross-sectional areas. The results of the T2 relaxation time (used as an index for hamstring activation) showed that the semitendinosus of the reconstruction side was a third less than the control side. The volume of the semitendinosus of the surgery side was 45% less than the control side, however the semimembranosus of the surgery side was greater than the controls. Overall, total hamstring volume was 9% less in the surgery side than the control side. For the ACSA, the semitendinosus was 28% lower in the surgery side compared to the control side, but the semimembranosus showed no between-limb differences. While the lateral hamstrings showed a 5% greater difference in the surgical limbs, the medial hamstrings were 11% lower for the ACSA in the surgical side compared to the control side. Overall, there was no statistical difference shown in the hamstrings for ACSA between limbs. For hamstring muscle lengths, the main finding was that the semitendinosus was 23% shorter in the surgical limb than the control. The rest of the hamstring muscles showed no significant difference in lengths between limbs. Looking at the ultrasound results after the exercise showed interesting findings. Of the 14 total semitendinosus analyzed, 7 showed partial loss of fibrillary pattern and 4 showed a complete loss of fibrillary pattern. Furthermore, distal semitendinosus muscle fascicles were only abnormal in the surgical limbs. The differences seen in muscle size and length could possibly be due to different rehabilitation strategies or the training done after being cleared as well as just having pre-existing differences before the surgery. Internal knee rotation strength has been reported to have deficits after ACL reconstruction surgery with a semitendinosus graft, which could explain the lower ACSAs and medial hamstring volumes on the surgical side. It can be concluded that the size deficit of the semitendinosus post-surgery could be due to limited stimulus to activate the muscle, even during the Nordic hamstring exercise, which specifically targets the muscle. It was suggested that rehabilitation programs include more exercises to increase the strength of other muscles, such as the semimembranosus to improve stability during knee internal rotation. Promoting semimembranosus hypertrophy through hip extension exercises compensates for the semitendinosus having a long regeneration process (18 months) post-surgery, with 10-50% of patients having no regeneration at all.

### 2.9 Summary

Currently, analyzing ACL injury risk factors is done with EMG and motion analysis, but IMUs offer on-field data analysis which can further help evaluate risk factors outside of a laboratory setting. It is important to consider the environment in which the athlete plays, their gender, and what difficulties each experience, when analyzing ACL risk factors and when returning to play after an ACL reconstruction surgery. Many biomechanical and neuromuscular risk factors for tearing an ACL exist, especially for females who are more prone to ACL injury. Furthermore, many deficits exist on the ACL reconstruction side. These deficits could be due to the structure of rehabilitation programs and the nature of the playing surface. Changes should be made to rehabilitation programs and/or return-to-play guidelines in order to get the athletes back to their safe game-playing abilities.

# CHAPTER 3 - METHODS

## 3.1 OVERVIEW

This chapter describes the methods used to collect tibiofemoral acceleration data and analyze ACL risk factors using IMUs and EMGs. Section 3.2 describes the inclusion criteria for selecting and recruiting subjects. Section 3.3 discusses the placement of the sensors for proper analysis. Section 3.4 explains the inside procedure. Section 3.5 describes the outside procedure. Section 3.6 describes the data analysis and section 3.7 describes the statistical analysis that is being used to test the collected data. Section 3.8 provides the summary of the chapter.

## 3.2 SUBJECT RECRUITMENT

Subjects were recruited through emails sent to athletic directors and by word of mouth. To be included in this study, participants had to be female biologically and be at least 18 years of age but less than 30. Furthermore, subjects had to participate in a turf sport of any level, which includes playing either collegiate, recreational, or intramural soccer, lacrosse, or field hockey. Next, subjects had to have previously torn their ACL, however, any contralateral ACL tears (tears on both legs) were not included in the study. Finally, subjects had to be medically cleared for contact by their physician and be free of any issues that would affect their ability to run.

## 3.3 SENSOR PLACEMENT

IMUs, EMGs, and motion analysis sensors were used. IMUs were placed above and below the knee in order to identify knee valgus moments and tibiofemoral acceleration. One sensor was placed on the proximal end of the tibia, which was on top of the tibial tuberosity, and the other on the distal end of the femur, equal distance above the knee. Sensors were placed in the same position on both legs in order to identify limb differences as shown in Figure 3.1.

EMGs were placed on three different muscles, including the rectus femoris, semitendinosus, and the biceps femoris on both legs, in order to identify hamstring to quadricep activation ratios. The hamstring muscles included the semitendinosus and biceps femoris and the quadricep muscle included the rectus femoris. Sensors were placed on the same muscles on both legs to identify differences between the two legs.

## 3.4 INSIDE PROCEDURE

Participants came to the Biomechanics and Gait Evaluation Laboratory (BaGEL) in the Beaver Athletics and Wellness Center on the Penn State Berks Campus. Upon arrival participants were asked for consent in participating in the study and provided with a copy of the Informed Consent Documents. Demographic data including height, weight, sport played, years of playing the sport, ACL reconstruction side, and date of surgery was collected (by questionnaire).

Subjects wore their own running shoes for the lab as well as their own cleats for on the turf. Subjects were asked to warm up on the treadmill at a self-selected running speed for a minimum of 2 minutes. After warming up, EMG sensors and IMUs were placed on the subject's legs.

Once participants were warmed up, maximum voluntary contractions (MVCs) were done for the EMG sensors to make sure they were on the correct muscle. After the EMGs were confirmed to be on the correct muscle, subjects took 5-10 practice runs across the 60ft lab runway to determine a comfortable running speed that matched their "game speed" and aligned their stride to the center of the runway where the cut marker was each run.

Participants ran 9 meters to the cut marker and performed the 120-degree cut at the marker and finished 1 meter after into another meter of deceleration. Breaks were taken between runs to walk back to the start. They continued this process until 6 successful trials were collected, 3 to each side. During these runs, EMGs measured their muscle activity and IMUs measured their limb acceleration.

### 3.5 Outside Procedure

After completing the inside portion, subjects were directed out to the turf field and put on their cleats before starting the outside portion. The same process was carried out on the Penn State Berks turf soccer field. There was a 9-meter run up to the 120-degree cut with the 1-meter finish into the deceleration. The same number of trials were done outside (6), with 3 to each side. Breaks were taken between trials as walks back to the start. During these trials, EMGs and IMUs were used to collect data.

### 3.6 Data Analysis

Data were collected and analyzed from the EMG and IMU sensors. From the EMG sensors, data were analyzed to see activation differences of the rectus femoris, semitendinosus, and the biceps femoris to assess the hamstring to quadricep activation ratio between legs. Furthermore, IMU sensors collected data on the tibiofemoral acceleration.

### 3.7 Statistical Analysis

Data were processed with SPSS programming. A two-by-two repeated measures Anova was used to analyze the data which compared the mean differences between groups in the SPSS program. The two-by-two part consists of the surface differences (turf vs. Lab) and injury (ACL reconstructed leg vs. healthy leg). Data were accepted as significant if the values were between $<0.05$ and $>0.001$.

### 3.8 Summary

EMGs, motion analysis, and IMUs were used to determine tibiofemoral acceleration and analyze ACL risk factors. Doing a cutting maneuver at the subject's selected game speed, subjects were put in game-like situations to mimic the real-life motion. Placement of the technology allowed for proper analysis of knee motion. Targeting specific muscles known to facilitate knee movement, analysis was done to see muscle activation deficits. Placing IMUs on either side of the knee allowed for analysis of tibiofemoral acceleration data. By using a two-by-two repeated measures Anova, direct comparison of the variables was done.

# CHAPTER 4- RESULTS

## 4.1 OVERVIEW

This chapter presents the results of the study. Section 4.2.1 discusses the tibiofemoral acceleration results and Section 4.2.2 discusses the muscle activation results. Section 4.3 is the summary of the chapter.

## 4.2 RESULTS

A total of 8 female athlete participants were included in this study. Of these 8, 5 played soccer, 2 played field hockey, and 1 played lacrosse. On average, the participants were 42 months (about 3 and a half years) post-operation ranging from 25 months (about 2 years) to 62 months (about 5 years) post-operation. Of the participants, 5 had an ACL tear on their left side and 3 on their right. In this study, 2 of the participants had a recurrent ACL tear (25% of participants) and 2 had a concurrent meniscus and ACL tear with reconstructive surgery.

Statistically significant results were anything $<0.05$ and $>0.001$. Anything above or below these were considered insignificant.

### 4.2.1 TIBIOFEMORAL ACCELERATION RESULTS

Tibiofemoral acceleration was compared between both the healthy and ACL reconstructed legs as well as between the lab and turf surfaces. Table 4.2 presents a summary of the results.

For the lab surface compared to the turf surface, the femur and the tibia had higher activation on the turf surface ($p=0.034$, $p=0.036$). Overall tibiofemoral acceleration had a significant difference ($p=0.038$) with acceleration being higher on the turf surface.

For the ACL reconstruction surgery leg compared to the healthy leg, overall tibiofemoral acceleration was statistically significant ($p=0.045$) with acceleration being higher on the ACL reconstruction leg. Furthermore, the femur was statistically significant ($p=0.043$) with acceleration being higher on the ACL reconstruction leg whereas the tibia was not statistically significant ($p=0.065$) between legs.

For the recurrent versus primary ACL reconstruction surgeries, all categories, except the femur, did not show a statistical significance. The acceleration of the femur ($p=0.046$) was higher for the recurrent group. The tibia ($p=0.056$) and the tibiofemoral acceleration ($p=<0.001$) were not statistically significant between groups, so neither had a significant difference in acceleration.

Figure 4.5 and Figure 4.6 present the average accelerations of each segment, left tibia (L Tib), left femur (L Fem), right tibia (R Tib), and right femur (R Fem) during the cutting maneuver to the left and to the right for both inside on the lab surface and outside on the turf. The data presented in the table were a summary of an ACL surgery on the left side.

**Table 4.1** Summary of IMU results. * Denotes a statistical difference

**TABLE 1**

| **Lab Versus Turf** | |
|---|---|
| **Femur*** | p=0.034 |
| **Tibia*** | p=0.036 |
| **Tibiofemoral Acceleration*** | p=0.038 |
| **ACL Surgery versus Healthy** | |
| **Femur*** | p=0.043 |
| **Tibia** | p=0.065 |
| **Tibiofemoral Acceleration*** | p=0.045 |
| **Recurrent versus Primary** | |
| **Femur*** | p=0.046 |
| **Tibia** | p=0.056 |
| **Tibiofemoral Acceleration** | p=<0.001 |

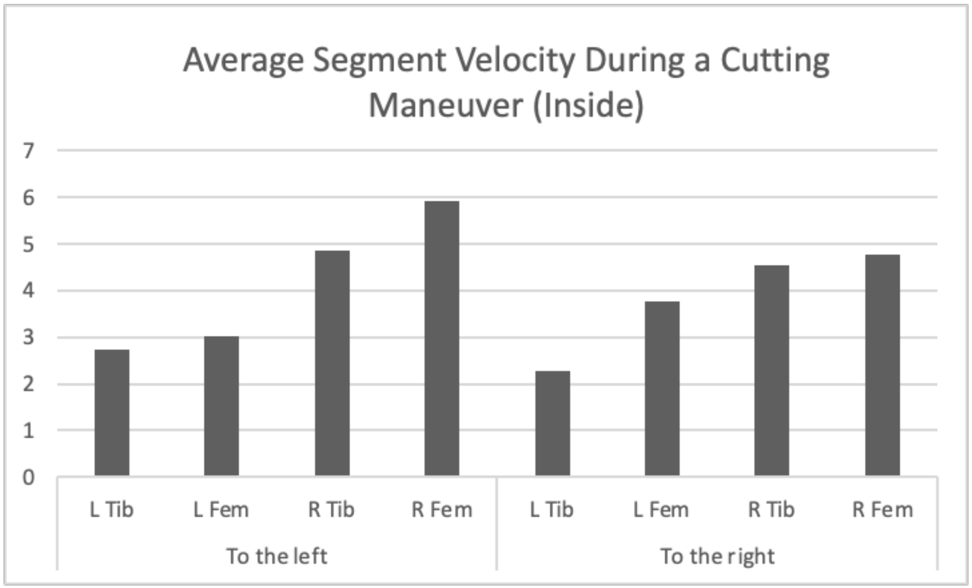


**FIGURE 1**

**Figure 4.1** Summary of average segmental velocity of the left (L) and right (R) Femur (Fem) and Tibia (Tib) for the lab surface (Inside).

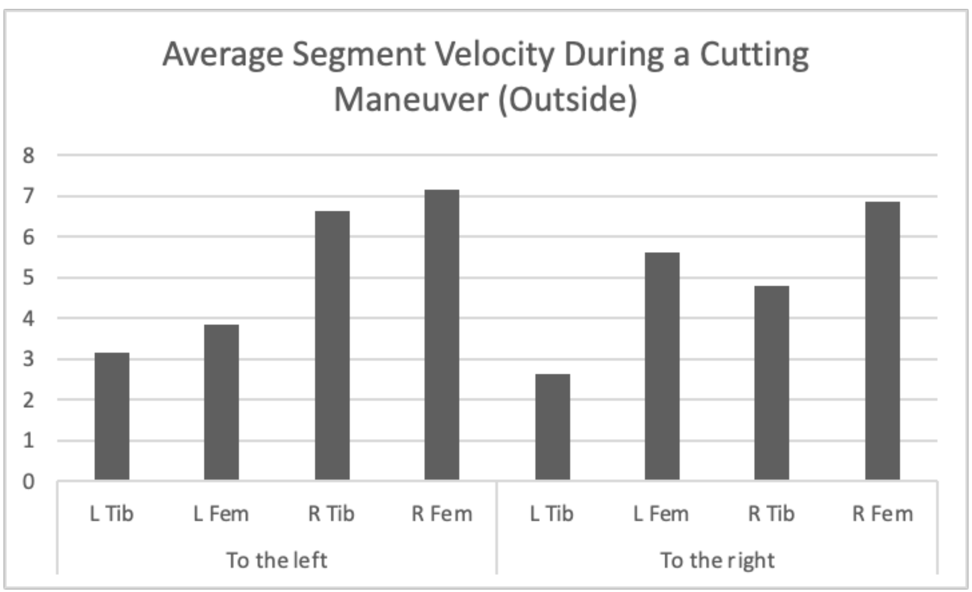


**FIGURE 2**

**Figure 4.2** Summary of average segmental velocity of the left (L) and right (R) Femur (Fem) and Tibia (Tib) for the turf surface (Outside).

### 4.2.2 Muscle Activation Results

Muscle activation was compared between the lab surface and the turf surface as well as between the ACL surgery leg and healthy leg. Further comparison was made between the recurrent ACL surgery and primary ACL surgery groups and also between the rectus femoris (RF) versus the semitendinosus (ST) and biceps femoris (BF) activation. The muscle activation results are summarized in Table 4.1.

For the surfaces (lab versus turf) the ST and RF showed a significant difference in activation (p=0.018, p=0.026) with activation being higher on the turf surface. The BF had no statistical difference between surfaces (p=0.067).

The ACL surgery leg only showed a significant difference for the ST muscle (p=0.034) compared to the healthy leg. The RF and BF did not show a statistical difference between legs (p=0.081, p=0.052).

For the recurrent ACL surgery group versus the primary ACL surgery group, there was again no statistical significance for the RF and BF muscle activations (p=0.067, p=0.069). However, the ST muscle did show a statistical significance in activation, with activation being lower in the recurrent group (p=0.047).

When comparing the quadricep muscle (RF) to the hamstring muscles (ST and BF), both the ST and BF had a significant difference. The ST versus RF was statistically significant (p=0.018) with activation being lower for the ST. The BF versus RF was also statistically significant (p=0.024) with the activation being lower for the BF.

Table 4.1 shows the muscle activation results of the BF, RF, and ST of both legs. Figure 4.1-4.4 present the muscle activation patterns of each of the muscles (BF, RF, and ST) during a cutting maneuver. Figure 4.1 is the muscle activation done on the lab surface with a cut to the right. Figure 4.2 is also done on the lab surface with a cut to the left. Figure 4.3 is done on the turf surface with a cut to the right. Figure 4.4 is done on the turf surface with a cut to the left. In all figures, the subject had a right leg ACL tear.

**Table 4.2** Summary of muscle activation results. * Denotes a statistical difference

**TABLE 2**

| Lab versus Turf Surface | |
|---|---|
| **ST*** | p=0.018 |
| **RF*** | p=0.026 |
| **BF** | p=0.067 |
| **ACL Surgery versus Healthy** | |
| **ST*** | p=0.034 |
| **RF** | p=0.081 |
| **BF** | p=0.052 |
| **Recurrent versus Primary** | |
| **ST*** | p=0.047 |
| **RF** | p=0.067 |
| **BF** | p=0.069 |
| **RF versus ST/BF** | |
| **ST*** | p=0.018 |
| **BF*** | p=0.024 |

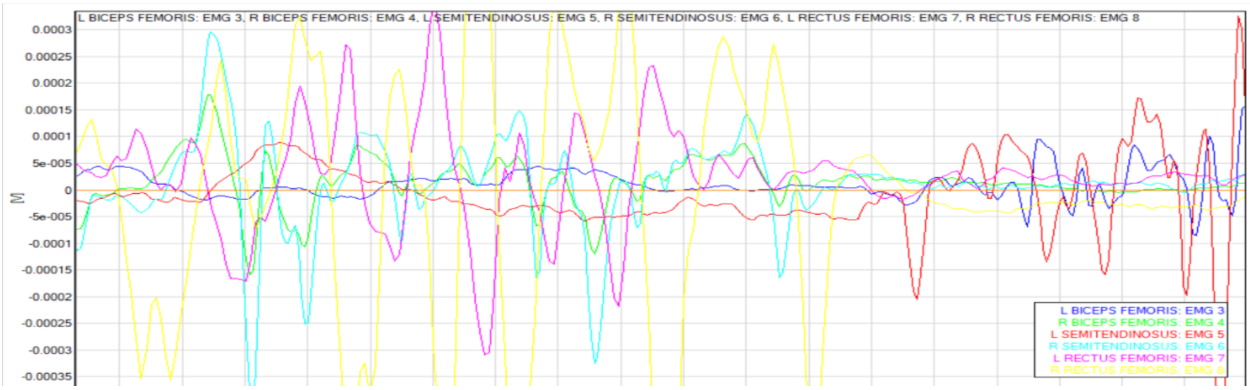


FIGURE 3

**Figure 4.3** Muscle activation of the BF, ST, and RF of both the Right (R) and Left (L) legs during a cutting maneuver done to the right on the lab surface.

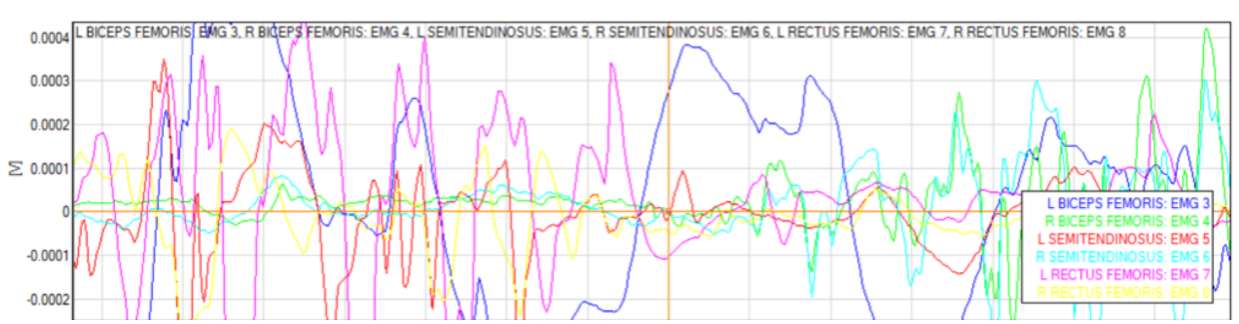


FIGURE 4

**Figure 4.4** Muscle activation of the BF, ST, and RF of both the Right (R) and Left (L) legs during a cutting maneuver done to the left on the lab surface.

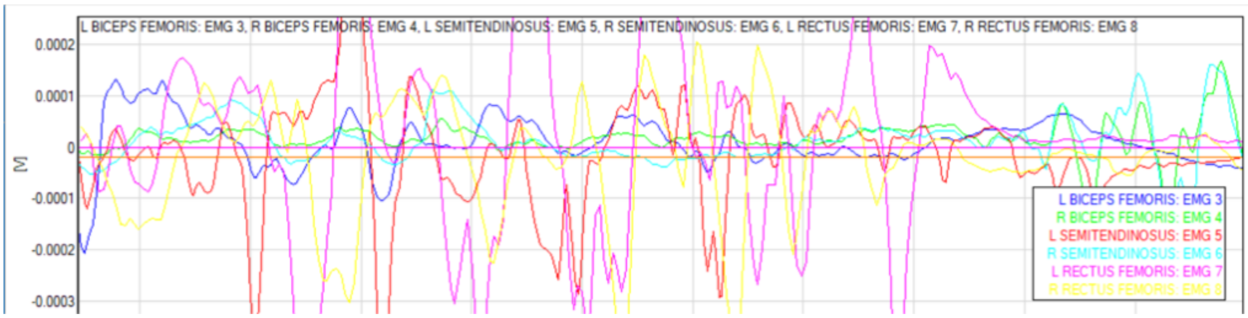


**FIGURE 5**

**Figure 4.5** Muscle activation of the BF, ST, and RF of both the Right (R) and Left (L) legs during a cutting maneuver done to the left on the turf surface.

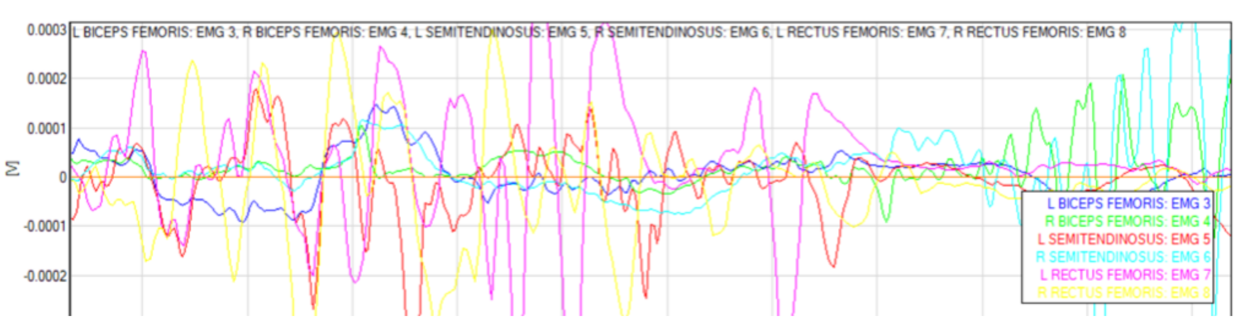


**FIGURE 6**

**Figure 4.6** Muscle activation of the BF, ST, and RF of both the Right (R) and Left (L) legs during a cutting maneuver done to the right on the turf surface.

### 4.3 Summary

The results of this study included a total of 8 females who participated in various sports. A significant difference was seen in tibiofemoral acceleration as presented in Section 4.2.1 as well as in muscle activation as presented in Section 4.2.2. The results of the IMU data were presented in Table 4.1. The results of the EMG data were presented in table 4.2. EMG activation of the RF, BF, and ST for each surface and direction were shown in Figures 4.3-4.6 Average segmental velocities were presented in Figure 4.1 and Figure 4.2.

# CHAPTER 5 - DISCUSSION

## 5.1 OVERVIEW

Results of this study show that women exhibit both biomechanical and neuromuscular risk factors post ACL reconstruction surgery that put them at a high risk for re-injury. Section 5.2 contains a discussion of the neuromuscular and biomechanical risk factors associated with previous ACL reconstruction surgery as well as the effects of artificial turf. Section 5.3 goes over the implications of the current study. Section 5.4 discusses the limitations of the present study. Section 5.5 recommends future studies. Section 5.6 presents the summary of the chapter.

## 5.2 BIOMECHANICAL AND NEUROMUSCULAR RISK FACTORS

In contrast to Kossin (2018), the biceps femoris did not see a higher muscle activation on the turf compared to the lab. However, the results of Besier et. al. (2003) coincides with the results of this study as the semitendinosus did see a significant difference between limbs and between surfaces, while the biceps femoris did not see a significant difference between surfaces even though it did between limbs. The recuts femoris did not show a statistical difference between limbs but did between surfaces. As discussed in Beaulieu et. al. (2009), the higher rectus femoris activation could be initiated to combat the instability of the knee. Since turf presents higher traction than the lab setting, the difference in rectus femoris activation between the surfaces could be to combat the extra knee valgus/varus and knee instability experienced on the turf surface.

In this study, 25% of the participants had recurrent ACL reconstruction surgeries and 25% had concurrent meniscus surgeries. Recurrent ACL reconstruction surgeries have been shown to have biomechanical and neuromuscular differences from those with primary surgery. The semitendinosus was the only muscle that had a significant difference in activation between the recurrent and primary groups. However, tibiofemoral acceleration was slightly higher in the recurrent group, which may be a result of the decreased semitendinosus activation. As shown by Sigward et. al. (2016) asymmetries and differences in knee loading mechanics are seen post ACL reconstruction, therefore putting increased risk of re-tear.

The turf surface overall showed having higher injury risk than the lab setting. With lower semitendinosus activation and the same rectus femoris activation on the turf compared to the lab surfaces, a result is a higher tibiofemoral acceleration, which causes increased anterior pressure and a higher risk for ACL strain/ tear on the turf surface. All athletes included in the study are accustomed to playing on a turf surface rather than a hard surface like the lab. As Steffen et. al. (2007) discussed, players can make adaptations to the surface on which they are playing, therefore a lack of quick adaptation can result in injuries such as ACL tears.

## 5.3 IMPLICATIONS

As shown by the results of the current study as well as the results of the studies mentioned in the literature review, caution should be taken when returning an athlete to full play.

Females specifically need to focus on strengthening hamstring muscles to have enough power to combat the anterior shear force (pressure) being put on the knee. This can be done either in rehabilitation programs for athletes post ACL reconstruction surgery or during strength training programs. Further prevention can be included in conditioning programs by integrating ACL tear prevention movements.

Return to play guidelines and physician clearances should also consider these results when allowing an athlete to return. An increased recovery time between non-contact and contact periods could be beneficial for the athlete reintegrating into the sport, especially when going back to playing on turf. Coaches should also be cautious of returning the athlete back to full play too early because the athlete's body may not be used to the strain of the movements and may take more time to recover. These precautions can lead to less overuse and recurrent ACL injuries.

## 5.4 Limitations of the Study

There were several limitations to the study. Due to the low number of subjects and the subject recruitment criteria, generalization to all sports, genders, and ages is minimal. Furthermore, the weather conditions were not taken into account during data collection. Since data collection was taken outside, weather could have an effect on the surface-shoe impact because wetter ground conditions on the turf field could result in less traction. Next, as mentioned by Tedesco et. Al. (2020), leg asymmetries prior to ACL reconstruction surgery were not taken into account, so deficits that were seen in the results also could have been seen prior to injury. Lastly, there was a lack of participants who were under 2 years post-operation. More recovery time could result in less deficits seen during data collection versus someone who had a more recent surgery.

## 5.5 Future Studies

Future studies include considering the type of ACL graft used in the surgery. The origin of the ACL graft could influence factors such as strength, endurance, recovery time, and post-operative pain. Furthermore, the effects of a semitendinosus graft for females can be explored to see if there are further deficits experienced. Future studies also could consider concurrent meniscus and ACL repairs and the effects they have on instability. They could also include current workout routines done by the subjects because putting emphasis on strengthening the hamstring muscles could result in a lower quadricep to hamstring activation ratio, which was unexpected in the current study. Leg dominance (as mentioned in Colby et al. (2000) and Hanson et. al. (2008)) could be taken into consideration in future studies in order to compare data between legs and to see if there is a higher likelihood that the non-dominant leg is more prone to ACL injury. Lastly, different weather conditions could be taken into account for surface-shoe impact. This could affect the amount of friction experienced between the subject and the ground and could cause a more slippery or sticky surface interaction.

### 5.6 CONCLUSIONS

Individuals with previous ACL reconstruction surgery pose a higher probability of re-tearing their ACL due to increased risk in biomechanical and neuromuscular risk factors. Women specifically show a lower hamstring to quadricep activation ratio and higher tibiofemoral acceleration during a cutting maneuver at 120-degree, putting extreme anterior strain on the knee. This strain increases the probability of tearing the ACL. Furthermore, artificial turf poses a threat to ACL injury due to the shoe-surface friction on impact.

These factors should be considered when implementing rehabilitation programs for athletes as well as recovery time and progress. Athletes should not be rushed back from ACL injuries post-reconstruction. Return to play protocols post ACL reconstruction surgery should be adjusted to the athlete's sport and consider the surface in which the athlete plays on.

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# ACADEMIC VITA

## Education

Pennsylvania State University Berks Campus, Schreyer Honors College
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## Undergraduate Thesis

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## Awards and Scholarships

August 2021 to present - Boscov Award
Spring 2020, Fall 2020, Spring 2021, Spring 2022, Summer 2022 - Dean's List

## Relevant Academic Experience

January 2023 to Present – Student in the Cadaver Laboratory
May 2022 to present - American Red Cross First Aid/ Safety and CPR/BLS Certification
January 2022 to Present – President of the Kinesiology Club
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August 2022 to March 2023 – Researcher in the Biomechanics Laboratory

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May 2022 to August 2022 - Internship in Physical Therapy Clinic at PIVOT Physical Therapy
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