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3D KNEE KINEMATICS AND KINETICS WITH VISUAL DISRUPTION IN SUBJECTS WITH ACL RECONSTRUCTION

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ABSTRACT

BACKGROUND AND PURPOSE: The anterior cruciate ligament (ACL) is a commonly ruptured ligament among male and female athletes. Women are at a higher risk of ACL injuries compared to men. The leading cause of female ACL injuries has been identified as non-contact mechanisms. Several risk factors for injury among females that have been theorized include: quadriceps/hamstring activation pattern and force production, greater dynamic knee valgus, hormonal influenced laxity and anatomical gender variation. The purpose of this research was to analyze three dimensional (3D) kinetic and kinematic dynamic landing patterns at the knee between ACL reconstructed and healthy females and any interaction effects of visual disruption.

METHODS: Seventeen healthy female subjects (25.3± 6 y) and 17 female subjects with an ACL reconstruction (26.5± 6.3 y) were studied. A 3D electromagnetic system measured knee position during a cutting maneuver from an athletic stance position. Anatomic boney landmarks on the occiput, sacrum, femur and tibia were digitized for capture. Subjects began on a force plate and were instructed to catch a ball and cut immediately left or right as indicated by a specific tone, which was randomized (40 trials). Vision was randomly disrupted via shutter glasses for either one second at the beginning of the cutting maneuver or was left intact for the duration of the movement. A two-way repeated measures ANOVA analyzed the differences between healthy and ACL reconstructed subjects and intact vision versus disrupted vision.

RESULTS: The results indicate significant differences exist between subjects with ACL reconstruction and healthy subjects for flexion, adduction, and external rotation knee angles and extension, abduction, and internal rotation moments. Significant interactions of group and vision conditions also exist for flexion, adduction, and external rotation knee angles. Vision alone displayed no significant differences for all subjects.

CONCLUSION: Years later, subjects with ACL reconstructions continue to display different knee kinematics and kinetics that could increase their risk for re-injury or injury of other leg. Furthermore, visual disturbances have significant effects on ACL reconstructed knee angles and moments when landing compared to healthy subjects. These results support continued movement related rehabilitation with visual disturbances for ACL reconstructed patients.

The undersigned certify that they have read, and recommended approval of the research project entitled:

3D KNEE KINEMATICS AND KINETICS WITH VISUAL DISRUPTION IN SUBJECTS WITH ACL RECONSTRUCTION

submitted by:

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in partial fulfillment of the requirements for the Doctor of Physical Therapy Program

Primary Advisor______________________________________ Date_____________

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CHAPTER I

INTRODUCTION

More than any other joint in the body, the knee joint depends on its ligamentous structures to maintain its integrity and act as primary stabilizers for guiding movements. The anterior cruciate ligament (ACL) provides the primary restraint for anterior tibial translation and vargus-valgus motion in full extension and rotation.[1] The ACL is commonly ruptured during sporting activities with an estimated 80,000 up to 250,000 injuries each year among men and women.[2] Women athletes are at a significantly greater risk of anterior cruciate ligament injury compared to their male counterparts participating in the same sports. In fact, women are at a 2 to 8 times increased risk for ACL injury compared to men.[3,4,5] The leading cause of female ACL injuries has been identified as non-contact mechanisms.[6,7] ACL injuries often occur under conditions of dynamic knee valgus with a tibial rotational component.[8] Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] reviewed the summary of the discussions and recommendations from the Hunt Valley II meeting that was designed to review and summarize data on ACL risk factors for injury, injury biomechanics, and injury prevention programs. The authors categorized the risk factors for ACL injury into anatomical, hormonal, and neuromuscular factors.[9]

First, Griffin et al.[9] reported on the anatomical risk factors for ACL injury. These consisted of body mass index, notch size, ACL geometry, and ACL material properties. Overall, geometric differences in shape and size of the ACL have not been well determined. Yet, it is accepted that a smaller ACL will experience greater stressors for a given load compared to a larger ACL. Also, a smaller ACL will fail at a smaller given load compared to a larger area ACL.[9] In two studies by Souryal and Freeman[10] and LaPrade and Burnett,[11] they both concluded that a smaller intercondylar notch was associated with increased risk for a noncontact ACL injury. Furthermore, the research shows female's ACL size has consistently been found to be smaller than males when normalized for weight.[10,11] A study by Anderson, Dome, Gautam, Awh and Rennirt[12] reported that when using MRI measurements to determine ACL size in high school basketball players, the ACL's in girls were smaller then the boys. Also, Chandrachekar, Slauterbeck, and Hashemi[13] found in a cadaveric study that females had a smaller ACL length, crossectional area, volume, and mass than male's ACL's. Even though the research failed to reveal differences between notch size between genders, the authors did report that larger male notches correlated with larger ACL size.[13] Overall, females tend to have smaller intercondylar notch sizes compared to males. This may be associated with smaller ACL masses and contribute to an increased risk for ACL injury.[13]

Due to an increase in the number of women experiencing ACL injury compared to men, there has been an increase in the research on hormonal aspects of ACL injury. Specifically, Yu, Liu, Hatch, Panossian, and Finerman[14] studied harvested cells from human ACL's that have been subjected to increased estrogen and progesterone levels. The authors looked at the cell proliferation and collagen synthesis in these ACL cell cultures and found a dose-dependent decrease in fibroblast proliferation and procollagen synthesis with increased estrodial levels.[14] Conversely, when estrogen was controlled for, they found an increase in fibroblast proliferation and procollagen synthesis as progesterone levels increased. These hormonal effects were most pronounced during the first one to three days of exposure, and plateaued around day seven.[14] This suggested that increases in sex hormones that occur during female menstrual cycles may influence collagen synthesis and ACL metabolism.[14]

Similarly, many studies have looked at the specific time during the menstrual cycle that the ACL injury had occurred. Wojtys, Huston, Boynton, Spindler, and Lindenfled[15] measured urine hormone levels in women to determine the exact cycle phase at the time of ACL injury. They reported that most injuries occurred during the ovulatory phase which is characteristic of high estrogen levels and occurs prior to the rise in progesterone levels.[15] In combination with Yu et al,[14] the time of higher estrogen levels appears to be associated with a decrease in fibroblast proliferation and procollagen synthesis of the ACL.[15] Therefore, the ovulatory phase of the menstrual cycle may present a risk for increased ACL injury in females. Slauterbeck, Fuzie, Smith, et al.[16] used saliva samples and questionnaires to determine where in the menstrual cycle females were experiencing ACL injury the most frequently. They reported the days immediately before and after menses were associated with a higher ACL injury rate.[16] Overall, there is no a clear agreement on the phase during the menstrual cycle that is associated with higher ACL injuries.

Hormones and their relation specifically to knee laxity and ACL injury have been linked to menstrual cycle as well. Research is limited in this area due to difficulty with exact timing and definitions of the phases of the menstrual cycle. Furthermore, hormones and knee laxity have been difficult to assess due to the variability in timing of females hormone changes. Shultz, Sander, Kirk, and Perrin[17] addressed these areas by assessing daily serum sex hormone concentrations for women throughout one complete menstrual cycle. The concentration levels were then compared to concentration levels of men which were measured once per week.[17] In addition; knee laxity was measured using a KT-1000 arthrometer. It was reported that female's knee laxity measurement varied the greatest during the luteal phase of the menstrual cycle; however, it was also noted that not all women were found to have an increase in knee laxity during hormone level changes.[17] Further research needs to be done to assess the implications of cyclic increases in knee laxity and their effect on risk for ACL injury. Overall, sex hormones effect on ACL injury risk has not been determined. Further research is needed on assessing the influence of sex hormone changes on ACL structure and knee joint laxity in order to determine the exact time during females menstrual cycles where they are at most risk for ACL injury.

Next, Griffin, Albohm, Arendt, Bahr, and Beynnon, et al.[9] focused on the biomechanics of ACL injuries. Specifically they address the biomechanical effects during dynamic loading and dynamic activities. The biomechanics of an ACL injury has been a common research topic for identifying possible causes for the increase in female ACL injuries. First, Griffin, Albohm, Arendt, Bahr, and Beynnon, et al.[9] reported that current literature has consistently found larger Q-angles in young adult women compared to young adult men. Also, Shambaugh, Klein, and Herbert[18] found that the mean Q-angles of athletes sustaining knee injuries were significantly larger than the players who did not get injured. The second biomechanical factor addressed was dynamic knee valgus. The landing position of the lower extremities in males and females has long been a common factor in ACL injuries.[18] Ford, Myer and Hewett et al.[19] used 3D analysis to assess dynamic knee valgus in high school athletes. The authors consistently found that female subjects land with significantly greater knee valgus then males.[19] Furthermore, a study by Hewett, Myer, and Ford[20] found that knee valgus measures were predictive of future ACL injuries. Lastly, a study looking at prepubescent, peripubescent and postpubescent males and females found that prepubescent males and females landed in valgus knee positions.[9] While peripubescent and postpubescent females continued to land in valgus, the male counterparts landed in varus knee positions.[9] The risk for ACL injury increases with valgus landing position because it places the ACL in and undesirable position that can lead to rupture.[9]

The third biomechanical factor reviewed was foot pronation. It is suggested that excessive foot pronation places the tibia in more internal rotation.[9] Woodford-Rogers, Cyphert, and Denegar[21] compared 22 female and male athletes with previous ACL injuries to 22 matched non-injured athletes of the same sport and position. Each subject’s navicular drop, calcaneal alignment, and anterior knee joint laxity were measures via a KT-1000 arthrometer. The authors used navicular drop as their measure of foot pronation.[21] They reported that greater navicular drops were noted in athletes with a history of ACL injury compared to those without ACL injury.[21] This suggests that as an athlete over-pronates their foot, they are at higher risk for ACL injury.[21] Furthermore, London, Jenkins, and London[22] compared 20 female athletes with ACL injuries with 20 age-matched controls on standing pelvic position, standing frontal knee position, standing sagittal knee position, hip position, hamstring length, prone subtalar joint position, and navicular drop. The authors found that the female athletes with history of ACL injury had a significant difference in their navicular drop, knee recurvatum, and subtalar joint position compared to the non-injured athletes.[22] This further demonstrates that excessive navicular drop may place individuals at a higher risk for ACL injury.

Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] reports that ACL injuries are generally thought to be associated with abnormal loading of the knee. Furthermore, they note that the principal factors related to the knee's loading pattern is the body's center of gravity and postural adjustment to external stimuli.[9] The dynamic loading of the knee refers to the loads being transferred across the joint that change over time and with the flexion angle.[9] There are many factors that influence dynamic loading including central nervous system factors, nerve-muscle interaction, muscle alone and the joint involved.[9] Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] describes the central nervous system factors to be focused on the patterns of movement and its association with learned behaviors, as well as the nerve-muscle interaction related to coordination and recruitment time of muscles. The individual muscle can affect the dynamic loading depending on the strength of contraction and amount of tension it can create.[9] Lastly, muscle activation can affect the dynamic loading of the knee joint, specifically time to peak torque, amplitude of contraction and the timing of the contraction.[9] All of these factors work together to influence the dynamic loading of the knee.

Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] reports on the positive and negative factors that affect the dynamic loading of the knee. The factors effect on the dynamic muscle control during loading of the knee include preparation for cutting, co-contraction of the muscles crossing the knee, and plyometrics with the intention to decrease time to peak torque of a contraction. Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] also reported on the factors that negatively affect the dynamic loading of the knee. These include muscle lower extremity muscle fatigue, muscle contraction imbalance, unanticipated cutting and landing with your hips and knees near full extension.[9] Many of these factors can be modified with training and therefore can decrease the risk of injury. Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] reported on the dynamic activities of the muscles associated with the knee joint. Anterior tibial translation has been a commonly accepted method of ACL injury. Wojtys, Wylie, and Huston[23] found that increased quadriceps activity over hamstring activity, hamstring weakness, decreased stiffness and muscle fatigue are all related to an increased amount of tibial translation. On the other hand, increased hamstring strength, knee stiffness, and muscle endurance are related to the least anterior tibial translation.[23] In two studies by Beynnon, Johnson, Fleming, Stankewich, and Renstrom[24] and Fleming, Beynnon, Renstrom, Johnson, and Perura,[25] ACL strain during various activities was assessed. Both studies found that ACL strain was higher during activities with the knee near full extension and with quadriceps or isometric hamstring contraction.[24,25] Conversely, ACL strain was lower during activities with the knee flexed greater than 50 degrees and with hamstring or isometric quadriceps contraction.[24,25]

Another area of research on ACL risk factors has focused on the neuromuscular aspects of these injuries. Specifically the altered movement patterns and muscle activation patterns. Griffin, Albohm, Arendt, Bahr, Beynnon, et al.[9] reports on numerous studies that have consistently concluded that women, in comparison to men, land jumping, cutting and pivoting maneuvers with increased valgus of the knee, increased internal rotation of the hip, increased external rotation of the tibia, less hip and knee flexion, less knee joint stiffness, and higher quadriceps contractions compared to hamstrings. Furthermore, it has also been reported that women have inconsistencies between their lower extremities in strength, flexibility, and coordination, also known as "leg dominance."[9] This difference between lower extremities has been related to an increase in ACL injury risk.[9] In a study by Yu, McClure, Onate, Guskiewicz, Kirkendall, et al.[26] it was reported that up until the age of 12 years old, boys and girls have the same knee flexion angles upon landing. It is after the age of 13 years old that girls are found to have a decrease in their knee flexion angle compared to boys.[26] This decrease in knee flexion angle upon landing jumps, cutting, and pivoting has been found to be a risk factor for ACL injury.[9]

Another important neuromuscular factor for ACL injury risk is the muscle activation pattern during jump, cut, and pivot maneuvers. The research has been consistent in finding that females have a higher quadriceps activation compared to hamstring activation during landing and cutting.[9] Malinzak, Colby, Kirkendall, Yu, and Garrett[27] found that female athletes had higher quadriceps activation and lower hamstring activation then males. With higher quadriceps and lower hamstring activity, females are at risk for uncompensated anterior tibial translation, placing the ACL in a position vulnerable to injury.[27]

In summary, anatomical, hormonal, biomechanical, and neuromuscular factors for ACL injury have been considered and highly researched. Overall, it is thought to be a combination of multiple risk factors that are contributing to the risk for ACL injury.

Purpose

Our primary purpose was to investigate specific 3-D kinematics of the knee during a cutting movement for female subjects with an ACL reconstruction compared to healthy subjects.

Operational Definitions

During left cutting, the left leg is referred to as the lead leg while the right leg is referred to as the lag leg. During right cutting, the right leg is referred to as the lead leg while the left leg is referred to as the lag leg. Peak Euler angle during the cutting movement represent the magnitude of the tibia in relation to the femur. Peak Euler angles for knee flexion and extension, knee internal rotation and external rotation, and knee abduction and adduction were collected during the cutting task.

1. Peak Euler angles for knee flexion and extension are represented by the y-axis. Flexion is represented as a positive number, while extension is represented as a negative number.

2. Peak Euler angles for knee internal rotation and external rotation in relation to the tibia moving on the femur are represented by the x-axis. Internal rotation is referred to as a negative number and external rotation is referred to as a positive number.
3. Peak Euler angles for knee abduction and adduction is represented by the z-axis. Knee abduction was represented using a positive number while knee adduction angles are represented using a negative number.

Hypotheses

Individuals with ACL reconstruction will display different 3D kinematics than healthy subjects during a cutting task.

1. ACL reconstructed subjects will have decreased flexion angles.
2. ACL reconstructed subjects will have more tibial abduction (increased dynamic valgus).
3. Tibial internal and external rotation angles are too variable to hypothesize.

CHAPTER II

REVIEW OF LITERATURE

Influence of Strength on ACL Injuries

When reconstructing the anterior cruciate ligament (ACL), there are different procedures used by surgeons across the country. It was originally thought that using a bone-patellar tendon-bone graft was ideal because patients generally demonstrated high initial strength, a faster healing time, and greater knee stability.[28,29,30] However, it has been debated whether the advantages of the bone-patellar tendon-bone graft outweigh the anterior knee pain, weakness of the knee extensors, and pain with kneeling that is commonly associated with this method. As a result, some surgeons are choosing to use an autogenous hamstring tendon graft because of the greater extension mechanism of the knee following this procedure.[31] Therefore, the objective of the Segawa, Omori, Koga, Kameo, and Iida, et al.[31] research was to perform further investigation of the rotational muscle strength availability in the surgical leg before and after surgically harvesting a semitendinosus tendon alone, or a semitendinosus and gracilis tendon.

The research was completed by further examining 62 participants who had underwent ACL reconstruction (ACLR) and had agreed to allow the measuring of rotational torque both before and 12 months after the surgical procedure. The participants had also followed a specific rehabilitation protocol following the surgery.[31] In 32 of the participants, the semitendinosus tendon was harvested while in the other 30 participants, both the semitendinosus and gracilis tendons were used.[31] In order to measure muscle strength both before and after surgical reconstruction, Segawa, Omori, Koga, Kameo, and Iida, et al.[31] used the Cybex 6000B machine to measure isokinetic peak rotational torque between legs at both 30˚/sec and 120˚/sec.

ACL reconstructed subjects who underwent harvesting of both the semitendinosus and gracilis tendons demonstrated a mean decrease of peak torque of the internal and external rotators at a velocity of 120˚/sec in the involved limb both before and after surgery.[31] In light of the event of harvesting both the semitendinosus and gracilis tendons, the authors speculated that the remaining internal rotators of the leg, the sartorius, popliteus, and semimembranosus tendons, would have to work harder to provide enough torque to internally rotate the limb.[31] As a result, it appears that the available muscles were not able to generate enough force to compensate for the loss. In addition to the overall mean loss of internal rotation strength, there was also a significant difference noted in the preoperative mean isokinetic peak torque produced in extension and internal rotation between the involved and contralateral limbs in both genders.[31] The authors noted, however that the weakness resolved in the male gender but not in females.[31] It was suggested that the difference may be due to the physiological knee joint laxity differences between genders. It is thought that the predominant internal rotational torque in women that is present prior to surgical repair may lead to a greater valgus alignment at the knee. Since the recovery of the internal rotational toque following surgery was insufficient, it is thought that the valgus position created by the medial hamstrings may be needed to prevent joint laxity.[31] In general, women typically demonstrate decreased muscle strength when compared to males, which can further complicate the need to compensate for harvested semitendinosus and gracilis tendons.[31] Even though bone-patellar tendon-bone grafts were not looked at, this research provides evidence that both the semitendinosus and gracilis tendons are necessary for a large internal rotation torque of the lower limb.[31] In patients where both tendons were harvested in order to repair the ACL, a significant decrease in internal rotation torque was noted and it was very difficult to compensate for this loss of function.[31]

In addition to the research on the appropriate surgical technique that should be utilized in order to benefit from the least loss of muscle strength,[31] Myer, Ford, Barber Foss, Liu, Nick, et al.[32] conducted research to determine the exact role the quadriceps and hamstrings play in a female ACL injury. The authors chose to focus on female athletes because previous research has shown that females activate the quadriceps without a matched activation of the hamstrings when performing drop landings.[33] This finding is in contrast to males who demonstrate comparative recruitment of both the hamstrings and quadriceps while performing knee-loading tasks.[34] Based on the thought that decreased hamstring recruitment compared to quadriceps recruitment may increase the risk for lower extremity injuries, it was suspected that in the female athletes recruited for the study, researchers would observe decreased knee flexion and increased knee extension strength.[32] In addition, the authors also speculated that in the participants with increased quadriceps strength and decreased hamstring strength, ACL injury would be more likely.[32]

In this study, Myer, Ford, Barber Foss, Liu, Nick, et al.[32] investigated isokinetic knee flexion and extension strength using a seated dynamometer in which the hip and knee were flexed to 90 degrees. Subjects performed 10, 300 degree repetitions of isokinetic knee flexion and extension on each leg.[32] Results indicate that, as expected, female athletes who injured their ACL did not increase their hamstring to quadriceps ratio during functional activities as their male counterparts demonstrated (P=0.04).[32] Another interesting finding that arose was that female athletes who did not injure their ACL demonstrated increased hamstring strength and decreased quadriceps strength when compared to their matched male controls.[32] These findings support previous research by Hewett, Myer, and Zazulak[34] in which it was postulated that decreased hamstrings strength which females exhibit in contrast to their male counterparts may be related to the neuromuscular imbalances and ACL injuries which are often noticed with maturation.

Flanagan, Galvin, and Harrison[35] also investigated the strength and force production between legs of an ACL reconstruction group (27±14.5 months post surgery) and a control group. It has been questioned whether ACL reconstructed patients will ever return to 100% following reconstruction and rehabilitation.[36] In order to study reactive strength and force production, Flanagan, Galvin, and Harrison[35] completed one, one hour testing session on 20 recruited subjects. Within each session, each subject completed performance testing including a single-leg hop-for-distance test and a 6-meter timed hop test.[35] In addition, the following four testing protocols were also completed using a force sledge apparatus to quantify the mechanical properties occurring at the knee: squat jump, countermovement jump, drop jump, and a rebound jump.[35]

In all four of the force sledge apparatus protocols, as listed above, participants started in sitting, secured to a chair while a harness was secured around their waist and over their shoulders. Participants were asked to perform at their maximum level, with their arms folded across their chest during all jumps. All subjects were asked to perform two practice jumps before performing three jumps on each leg for each condition. Subjects were allowed a one minute recovery time between each jump in each of the four force sledge protocols, while two minutes of recovery were allowed between each test of the force sledge protocol jumps.[35]

While performing the squat jump from the original seated position, participants were asked to place their feet on a force plate while they lowered themselves into 90 degrees of knee flexion as determined with a goniometer using the greater trochanter and lateral epicondyle as landmarks.[35] Once patients were steadied in the starting position, they were asked to jump straight upward, using maximal effort, while the force plate was used to collect ground reaction forces. The countermovement jump was initiated from the original seated position and patients were again asked to place their foot on the force plate that was used during the squat jump procedure; in this situation, however, their knee was fully extended.[35] Participants were then asked to jump as high as possible. While performing the drop jump from the initial seated position with their foot, again, placed in the force plate apparatus, each seat was lifted to a drop height of 0.30 m above the force plate. Participants were given a 3-2-1 countdown and were then released to drop onto the force plate. Subjects were instructed to land with their legs extended and then jump quickly off the plate.[35] Finally, while performing the rebound jump, participants, again, started in the seated position with their foot on the force plate. As in the drop jump, subjects were raised to a height of 0.30 m above the force plate and following a 3-2-1 countdown, were released to drop toward the force plate. Upon contact with the force plate, each subject was instructed to perform 4 maximal jumps, in succession.[35]

Flanagan, Galvin, and Harrison[35] wanted to determine if a full recovery of a previously torn ACL was possible. Strength production was assessed by comparing the ACLR group's involved and uninvolved legs, as well as comparing the difference between the involved and uninvolved legs of the ACLR group to a control group.[35] Their data revealed no significant differences between groups in the single-leg hop-for-distance test or the 6-m timed hop test.[35] While using the force plate apparatus to measure strength and force production, a significant difference (P=0.041) was observed between legs in the ACLR group, as the uninvolved leg generated more force during the squat jump.[35] Since this difference did not translate into a performance deficit, it was considered an unimportant finding.[35] In addition, the authors were unable to find any other significant differences during the drop jump, rebound jump, or countermovement jump.[35] Subjects who were 27±14.5 months post surgery and underwent ACL reconstruction with intense rehabilitation did not appear to present with overall significant deficits in strength or force production.[35] Therefore, it appears that with intense rehabilitation, subjects recovering from an ACL reconstruction can both regain their between-legs force production and strength capabilities as well as jump to comparable heights of a healthy subject.

As noted above, many studies have examined the return to function following injury to the anterior cruciate ligament. It has been thought that injury to the ACL results in long-term mechanical and functional instability.[37] In order to perform further analysis on the ability to perform functional activities following ACL reconstruction, Mattacola, Perri, Gansneder, Gieck, Saliba, et al.[37] used the Biodex Stability System (BSS) to compare postural stability, single-leg hop, and isokinetic strength measurements in both an ACLR group (18 ± 10 months post surgery) and a control group. The BSS is a computer device developed to measure closed-chain neuromuscular control.[38] The advances of the BSS allow for researchers to more extensively study postural stability by analyzing normal joint motion, something that the force plate apparatus did not allow.[37]

Subjects were tested for postural stability, strength, and single-leg hop tests in a randomized order to avoid a learning effect.[37] Mattacola, Perri, Gansneder, Gieck, Saliba, et al.[37] tested participants for single leg and bilateral postural stability by measuring the deviation of foot position coordinates while standing on a moving platform for 30 seconds; measurements were taken in both the anterior-posterior and medial-lateral planes. The BSS platform contains six different moving levels, from level 6 being the most stable to level 1 being the least stable.[38] Single-leg hop for distance tests were also performed by Mattacola, Perri, Gansneder, Gieck, Saliba, et al.[37] in order to test for strength and confidence in each leg. During the three trials performed on each leg, each subject was asked to start at a pre-determined line on a randomly chosen leg, hopping as far as possible, landing on the same leg. Subjects were encouraged to use arm swing in order to put-forth maximal effort. After the three tests were performed on each leg, the best distance was recorded in centimeters for each leg.[37] In addition to the above two tests, concentric and eccentric knee flexion and extension strength testing was also performed in the seated position on each leg, using a Kin-Com dynamometer which was preset at 120° per second and 240° per second.[37] Extremities and velocities were counterbalanced to prevent fatigue and a learning effect.[37] Subjects were allowed four practice repetitions at each velocity at 75% of their maximal strength.[37] Following a two minute rest period after the practice session, each subject performed three maximal concentric and eccentric repetitions, at each preset velocity, on each leg.[37]

In this research, Mattacola et al.[37] found no significant differences between groups for postural stability. The study did reveal, however, that strengthening of the quadriceps following ACL reconstruction was vital.[37] ACL reconstruction subjects demonstrated deficits in both hop distance ($P<0.05$) and involved limb quadriceps strength ($P<0.01$) when compared between groups. ACLR subjects hopped a significantly shorter distance on the reconstructed leg than with the healthy leg ($P<0.01$).[37] These results suggest that ACLR subjects may develop increased strength on the uninvolved leg which is also known as a compensatory mechanism after the injury.[37] The authors suggest that the noted strength differences and lack of postural instability may be a result of the specificity of the single-leg hop.[37] Since this test requires specific strength of the quadriceps, a decreased loading capacity and ability to generate force is noted when quadriceps strength is decreased.[37] However, while measuring postural stability, the authors postulate that this task may not have been as challenging because balance requires activation of much of the lower leg musculature, not just the quadriceps. As a result, they suggest that clinicians focus on strengthening the quadriceps femoris in addition to the much researched hamstring musculature. An increased focus on strengthening the quadriceps musculature may result in increased performance and earlier return to function.[37]

Ahmad, Clark, Heilmann, Schoeb, Gardner, et al.[39] studied the effects of gender and maturity on quadriceps-to-hamstring strength. They wanted to determine the appropriate time to initiate anterior cruciate ligament injury prevention programs with females and males. During quadriceps contraction, there is an anterior-directed force on the tibia relative to the femur. This shear force puts the ACL in an undesirable position that places it at risk for rupture.[39] It has been proposed that the hamstrings contribute to decreasing this risk of ACL rupture by reducing the translation of the tibia caused by the quadriceps contraction. Therefore, if hamstring strength is inadequate to combat the quadriceps contraction, there is increased risk for ACL injury.[39]

Male and female subjects between the ages of 10-18 years old were examined for general ligamentous laxity, the tibial anterior translation in relation to the femur with the Lachman test, using a KT-1000 arthrometer, and quadriceps and hamstring strength. The subjects were separated into four groups to examine gender differences with maturity. The mature boys, 14 years and older, were found to have significantly less joint laxity when compared to the immature boys of ages 13 years and younger, the immature girls who were premenarchal, and the mature girls who were 2 or more years after menarche. Thus, males were found to have a decrease in joint laxity as they age, but this was not found with females. Prior research has been inconsistent in determining if increased ligamentous laxity is related to increased knee injuries.[39]

Ahmad, Clark, Heilmann, Schoeb, Gardner, et al.[39] also reported that both males and females had an increase in quadriceps and hamstring strength with age. However, boys demonstrated a greater increase in hamstring strength with maturity compared to females. Anderson, Dome, Gautam, Awh, and Rennirt[12] also found that female athletes had weaker hamstring muscles compared to quadriceps muscles. In addition, the present study found that when considering quadriceps-to-hamstring ratio, mature girls had a greater ratio than immature girls, immature boys, and mature boys.[39] This indicates that mature girls had weaker hamstring muscles than their quadriceps. This was attributed to a greater percentage of increase in quadriceps strength compared to hamstring. In contrast, male athletes experienced a greater percentage increase in hamstrings strength compared to females.[39] Therefore, the present study identified the discrepancy between quadriceps and hamstring strength with maturity. Female athletes are experiencing anterior tibial translation from a stronger quadriceps contraction, with significantly less opposition of this movement by the hamstrings. This anterior tibial translation places female's knees in an undesirable position for the ACL, and increases its risk for rupture.[39]

ACL Injuries and the Influence on Gait

Devita et al.[40] proposed that learning to adapt to the changes of joint kinematics, kinetics, and energetics during walking should occur within 2 weeks after the initial ACL injury. It was thought that if the changes were not observed within this time period, external factors such as different rehabilitation protocols or a knee brace may be necessary to learn the needed adaptation changes.[40] Nine subjects who underwent arthroscopic ACL repair using a bone-patellar tendon-bone graft volunteered to participate in the experimental group while ten healthy subjects with no history of lower extremity pathology volunteered for the control group. Subjects were tested 2 weeks after the injury, 3 weeks after surgery and 5 weeks after surgery.[40] At each testing time, eight separate walking trials were conducted using an AMTI force platform to measure ground reaction forces at the knee and hip joints and a video camera to capture details in the sagittal plane.[40] In order to gather the data, the authors placed reflective markers on the lateral side of the heel and fifth metatarsal, and on the injured side of the femoral condyle, greater trochanter, and shoulder.[40] Results indicate that there were no significant differences in stride characteristics between groups before surgery or 5 weeks post surgical reconstruction, but that ACLR subjects were more flexed at the hip and knee.[40] This indicates that the joint torque adaptations that are necessary to develop following ACL reconstruction require a long period of time to solidify. In addition to this finding, a significantly increased knee extensor torque was noted in the injured limb throughout stance phase before surgery and up to 3 weeks post surgery ($P<0.001$).[40] While healthy subjects generated hamstring activation followed by quadriceps activation to prevent tibial translation, patients who had an acute ACL injury and repair activated the quadriceps first. On the other hand, patients who had a more chronic ACL tear and then underwent reconstruction generated the hamstrings first followed by activation of the quadriceps.[40] This finding leads to important information in ways to structure rehabilitation programs. It is thought that by focusing on increasing hamstring strength, rehabilitation programs will be able to decrease the extensor torque at the knee which was shown in this study. Reducing this knee extensor torque can decrease the chance of further injuring the reconstructed ACL by reducing the stress placed on the ligament.[40]

In another study by Knoll, Kocsis, and Kiss,[41] gait patterns were examined in healthy and acute and chronic ACL deficient participants prior to and 6 weeks, 4 months, 8 months, and 12 months after ACL reconstruction. The authors[41] used a 3D ultrasound-based CMS-HS system to analyze the gait patterns of patients following ACL reconstruction using a bone-patellar tendon-bone graft. Subjects walked for 6 minutes to familiarize themselves with the machine then continued to walk for an additional 10 minutes at 2 km/hr. During this time period, EMG data was collected from the vastus lateralis, vastus medialis, biceps femoris, and adductor longus of bilateral lower extremities.[41] In contrast to what was expected, Knoll, Kocsis, and Kiss[41] were unable to report evidence that a quadriceps avoidance pattern, a pattern in which the knee remains in a flexed position with decreased quadriceps activation throughout gait, occurs in individuals who are ACL deficient. Rather, what was found was that the chronic ACL deficient participants, who went on to have an ACL reconstruction, demonstrated comparable knee characteristics as the control group. Results showed that even though acute ACL deficient subjects who went on to have an ACL reconstruction may present with a quadriceps avoidance pattern for up to 6 weeks after surgery, the occurrence does not exist in the chronically deficient ACL population.[41] The authors[41] speculated that this interesting finding may be due to increased vastus lateralis and medialis firing in order to prevent tibial rotation. In addition, another possible explanation for the noted time lag of the patients who had an acute ACL tear reconstruction may simply be a result of the thought that increased time is needed to develop gait adaptations for the reconstructed knee.[41,40] In fact, EMG data from the current study reveals that it may take as long as 8 months for the muscles of the lower extremity to return to their pre-injury functioning level.[41]

Repercussions on Proprioception Post-ACL Injury and Surgery

After an ACL injury, knee instability leading to insufficiency in body balance and movement quality is found and this is thought to be because of permanent damage to the sensory functions of the ACL. After ACL reconstruction surgery, these deficits prevail. Vibration is a simple stimulus that can influence proprioception receptors and possibly help to return normal function to individuals with deficits. Brunetti, et al.[42] investigated a new method of applying vibratory stimulation in order to permanently restore balance and motor function in patients that have undergone ACL reconstruction.

Brunetti, et al.[42] performed a double blind randomized study of 30 males in their mid 20s with recent ACL reconstruction. Fifteen participants were put in the stimulated group, which consisted of conventional therapy and mechanical vibratory treatment. The vibratory treatment was performed with CRO SYSTEM, which is a device made by NEMOCO srl, Italy. The participants received the vibratory stimulation on the skin over the distal portion of the quadriceps above the patella while they were asked to continuously hold an isometric contraction for the treatment at about 50% of their MVC. The vibratory parameters used were 100Hz frequency, 4-6N force, and 5-15um amplitude.[42] There were three applications of vibration applied for 10 minutes each with

30 second intervals between, for three consecutive days one month post surgery. The control group also had 15 participants, who received conventional therapy and placebo vibratory treatment. Both the control and the stimulated group received equal time in conventional therapy that was standardized and progressive in order for participants to return to running and light sport activity. Both groups also had the same time of vibratory treatment, however, the placebo treatment consisted of the vibratory machine being held above the skin with no contact.[42]

Brunetti, et al.[42] measured the participants at 1, 10, 90, and 270 days post treatment to evaluate the effectiveness of vibratory treatment. Several outcome measures were utilized: center of pressure signal from a force plate with single limb balance and eyes open and single limb balance with eyes closed, dynamometer for extensor peak torque, 2000 IKDC subjective knee evaluation form, and SF-36 quality of life self evaluation.[42] When measuring with the force plate, the participants were told to stand on one leg with their knee flexed at 15º, their hip in neutral, and their arms crossed over their chest. They remained still for 20 seconds while mean speed shifts and ellipse area were measured. Participants had a short training period and then performed this test on both the operated and non-operated leg, with the order being randomized for which to use first. The isokinetic evaluation with the dynamometer was performed while participants were sitting and determined the quadriceps muscle torque at 90º/s between 90º and 20º. The participants were given 15 warm up trials and then were allowed to perform this test until they were unable to increase their torque. The highest three scores achieved were used for analysis.[42]

After 270 days, the stimulated group had statistically significant results compared to the control group in all areas except single limb balance with eyes open, which was attributed to vision playing a large part in balance and the participants not having to utilize the proprioception at the knee.[42] The single limb balance with eyes closed showed a reduction in elliptic area amplitude of 40% and a reduction in velocity of 27% in the stimulated group, compared to 12% and 18% in the control group. Next after 270 days, there was a deficit of 6% of extensor peak torque on the operated side compared to the non-operated side for the stimulated group, whereas for the control group it was 28%. It was further noted that these differences were seen quickly, appearing at 3 months post surgery, and then both groups increased at similar rates, keeping the divergence between them.[42] The SF-36 results for the stimulated group were 15-20% higher than the control group. The 2,000 IKDC results were 20-25% higher for the stimulated group as well. The results show that the group receiving the vibratory treatment made improvements in strength and proprioceptive control quickly as compared to the placebo group.[42] Vibratory treatment, as used by Brunetti, et al.,[42] coupled with standard therapy improves single leg standing balance and extensor muscle torque on the operated ACL leg. This information is clinically important because balance is an important factor in the prevention of re-injury.

With an ACL injury, the integrity of the knee is altered. This leaves the individual with lasting functional deficits, even after reconstructive surgery. It is thought that these lasting deficits are the result of altered sensory and proprioceptive activity of the injured ACL. With this in mind, Cooper, Taylor, and Feller[43] designed a randomized control study to compare the differences between a proprioceptive and balance rehabilitation program against a traditional program focusing on strengthening. They[43] focused their research on the early phase of rehabilitation following an ACL reconstructive surgery. Cooper, Taylor, and Feller[43] randomly assigned 29 post operative ACL reconstructive surgery patients ages 16-50 into a balance and proprioception group or a strengthening group. Both groups received equal intervention time of 60 min per session, 2 times per week, for 6 weeks, and having a one hour per day home exercise program. At the initial assessment, it was found that the groups were not equal at baseline for age, flexion ROM, and their Cincinnati knee rating system for pain and squatting/kneeling, so change from baseline to final scores were looked at instead of between group comparisons. Several outcome tools were used to measure changes within the different intervention groups: Cincinnati knee rating system, patient specific functional scale, knee range of motion, single leg hop test for distance, timed single leg hop over 6 meters, and the single leg cross over triple hop for distance test. The participants were also asked to keep an exercise journal to monitor their compliance in order to find out if that would be a factor affecting the end results.[43]

The intervention time for each group was set up equally, however each group had a specific intervention protocol designed to focus on only balance/proprioception or strength. The balance and proprioception groups were given exercises based on and modified from previous exercises used in ACL studies on proprioceptive rehabilitation. These exercises stressed a stable balance position maintenance for greater than 20 seconds.[43] The exercises were later progressed to increase the balance challenge, such as decreasing their base of support or closing their eyes. Some examples of exercises given are standing on a mini trampoline, balancing on wobble board, bridging on a Swiss ball, and single leg stance throwing a ball. The strengthening group received a modified protocol of Brunkner and Khan,[44] where most exercises were designed to strengthen the major lower extremity muscle groups. A set-repetition structure was set up individually for the participants with the goal of working the muscles to the point of fatigue. When progression was necessary, the resistance was increased.[43] Some examples of exercises given were biking with moderate to hard resistance, split squat, forward lunges, single let bridges, and hip abduction side lying with weights.

After the 6 weeks of rehabilitation, both groups were reassessed and the change scores were compared. Statistically significant results were seen for the strength group compared to the proprioception and balance group based on the Cincinnati knee rating system for swelling (p=0.047), walking (p=0.04), and squatting/kneeling (p=0.01), and for the patient specific functional scale for activity 2 and activity 3 (p=0.01).[43] No statistically significant differences between groups were seen in the Cincinnati knee rating system for pain, overall condition, stairs, patient specific functional scale for activity 1, AROM in flexion or extension, single leg hop for distance, timed single leg hop over 6 meters, or single leg cross over triple hop for distance tests.[43] Cooper, Taylor, and Feller[43] concluded that there was only slight improvement with the strength training group compared to the balance and proprioception training to improve function in the early stages of rehabilitation after an ACL reconstruction. These results suggest that clinically there is no benefit of doing one program over the other for function. This is only the second study that has investigated the difference between using proprioception and balance versus strengthening, and the results of this study[44] compliment the first study done by Liu-Ambrose et al.[45], which also concluded there were no additional benefits found for either one program over the other.

ACL injuries disrupt the knee joint and lead to altered sensorimotor control. Due to weight bearing and ROM restrictions after ACL reconstruction therapy, proprioception rehabilitation is delayed usually three weeks.[46] This thought prompted Friemert, et al.[46] to investigate the difference between using Continuous Active Movement (CAM) or Continuous Passive Movement (CPM) on a patient's Joint Position Sense (JPS) post ACL reconstruction surgery. The CAM was theorized to improve a patient's JPS due to the patient having to actively use their leg, causing the sensorimotor system to have increased stimulation compared to passive movement.[46] The CAM therapy incorporates closed kinetic chain training and muscular coordination, which are accepted principles for proprioceptive training.[46]

Friemert, et al.[46] used 60 post ACL surgery patients and prospectively randomized them into two equal groups, CAM and CPM. The objective was to see if within the first seven days after surgery, the CPM or CAM produced better JPS in the patients. All patients in this study received equal care of standard hospital physical therapy, lymphatic drainage daily, and three hours a day in their assigned machine (CPM or CAM).[46] Passive angle reproduction test, as described by Jerosch and Prymka,[47] was used to determine the patients' JPS. Pain was also assessed using a visual analog scale and ROM was assessed using a goniometer. Both pain and ROM did not show any statistically significant differences between CPM or CAM groups.[46]

It was found that CAM had a significant impact on JPS compared to CPM, with the CAM group showing almost normal levels of control.[46] The CAM group preoperatively showed 5.7±2.4º difference side to side and after seven days showed 2.0±1.2º, whereas the CPM group originally showed a side to side difference in JPS of 5.9±2.2º and after seven days it was 4.2±1.6º.[46] Non-injured individuals showed 1.5±.07º difference between sides, which is not statistically different from the CAM group seven days post operation.[46] This shows that the CAM therapy brought the patients back to near normal levels of JPS. This finding is clinically significant because JPS has a high correlation with improved performance on tests like the single leg hop and vertical jump test.[46] However, one downfall of this study was that no long term follow up was completed, leaving the long term effects and differences between CPM and CAM unknown.

Certain neuromuscular movement strategies used in sports and high impact activities lead to lower extremity joint mechanics that could lead to injury. It has already been shown that tasks to predict ACL injury risk in young female athletes exists, such as lower extremity valgus during jump and landing tasks.[48,49] It is also thought that during dynamic movements, sagittal plane motions and certain load patterns contribute to the higher rate of female athlete ACL injuries. Since there is knowledge of what movement patterns predispose an athlete to injury, correcting those patterns with training should decrease the athlete's risk.[48,49] Myer et al.[50] designed a study to compare the effects of plyometric jumping exercises versus dynamic stabilization and balance exercises on female athlete lower extremity kinematics during landing tasks.

Using a high school volleyball team, Myer et al.[50] randomly assigned eight participants to the plyometric training and 10 to the balance training. It was determined that there were no significant baseline differences between groups and that there was adequate power for the results. Both groups received equal attention in the specific training they were assigned to as well as general strength training. Specific protocols with explicit activities and dosages were given to both groups at 1, 3, and 5 weeks.[50] Some exercise examples from the plyometric group include wall jumps, bounding in place, squat jumps, power steps, box drop, and barrier hops. Some exercise examples from the balance group include single leg squat, BOSU crunches, single leg line hop, swiss ball squats, and Airex walking lunges. Using the dominant limb as the limb used to kick a ball, the outcome measures were taken with a 3D kinematic testing unit to measure drop vertical jumping and medial drop landing.[50] Coronal and sagittal plane measurements were taken at the hip, knee, and ankle (flexion, abduction, inversion, eversion, rotation) as well as general initial contact information and toe off.[50] Two force plates, eight high speed eagle video cameras, and a box to jump from were utilized to gather data.[50] After 6 weeks of specific training both groups showed improvements on the tests. There were statistically significant changes in both groups with decreases in coronal plane movement during the vertical jump test in initial contact, maximum hip adduction angle, and maximum ankle eversion angle.[50] There were statistically significant decreases in the coronal plane movement during the medial drop landing for both groups in initial contact and maximum knee abduction angle.[50] There were no statistically significant differences between the two groups during these tests in the coronal plane.[50] This suggests that both plyometric and balance training may help to decrease risk of ACL injuries due to excessive coronal plane movement.

There were statistically significant results in the sagittal plane movements as well. During the vertical jump test, the plyometric group increased the sagittal plane movements in knee flexion at initial contact and maximum knee flexion angle. Whereas there was an increase in sagittal plane movement during the medial drop landing in the balance group at maximum knee flexion angle.[50] These results show that sagittal plane angles at the knee are task specific, so both types of exercise would be beneficial in an injury prevention program for female athletes.[50]

When looking at knee proprioception studies, confusion may arise due to the lack of having one standardized test. Without standardization, it is very difficult, if not impossible, to compare studies and understand seemingly conflicting results. Roberts et al.[51] note that three common tests are commonly used to measure proprioception, but all three had rarely been compared in one single study or to one group of participants. These three tests are: measurement of threshold to detection of passive motion, active reproduction of passive angle change, and visual estimation of a passive angle change.[51] Roberts et al.[51] designed a study to compare proprioception in patients post ACL reconstruction with their non surgical leg as well as with other healthy age and gender matches. Roberts et al.[51] used 20 patients, 15 male and 5 female with an age range of 19-38, and a reference sample of age and gender matched individuals, 14 male and five female with an age range of 20-37. The patients had undergone a single ACL reconstruction and participated in traditional therapy that focused on regaining ROM, strength, endurance, and coordination of limb movement, while the reference sample had to have no history of lower extremity injuries or any disease that might interfere with neural function.[51] Comparisons were made between the patients' operated leg versus the non-operated leg and between the patients' operated leg versus the reference population using three different proprioception outcome measures: Threshold Test, Visual Estimation Test, and Active Reproduction Test.[51]

The Threshold Test was performed moving toward extension and toward flexion from both 20º and 40º. Participants closed their eyes and noted when they felt that their leg was moving. The tester had a motor move the participant's leg at 0.5º/sec.[51] The Visual Estimation Test had the patients remember the starting position of their knee visually, which was 60º for the extension trial and 30º in the flexion trial. Then the tester had the machine move their knee 30º at 0.5º/sec. The participant was then given a protractor with the original starting position and asked to move the plastic leg to what they thought was the new position of their own leg.[51] The Active Reproduction Test used the same beginning positions as the Visual Estimation Test. The tester then manually moved the leg at about 10º/sec until the final position for the leg. This was held for a moment and the participant was told to remember the position of the leg. The examiner moved the leg back to the original position and asked the participant to actively move their leg back to the end position. [51] The median of three consecutive trials was taken for data analysis in all three methods of measurement.

In their study, Roberts et al.[51] found statistically significant results between the surgical leg and the reference population on the Threshold Test in 20º toward extension (p=0.0003), 40º toward extension (p=0.0448), 20º toward flexion (p=0.0037, and 40º toward flexion (p=0.0008), as well as between the non-surgical leg and the reference population on the Threshold Test in 20º toward flexion (p=0.0018) and 40º toward flexion (p=0.0220). These results suggest that there is indeed a deficit in knee proprioception post ACL injury and surgery, but also that there is a deficit bilaterally in these individuals compared to a healthy reference population.[51] Due to the possibility of a bilateral deficit, using the non-surgical leg as a reference leg may not be ideal for future studies. Also, individuals with an ACL injury may be more prone to re-injury or injuring the other leg due to the proprioception deficits. There were no statistically significant results between any of the comparisons using the Visual estimation Test or the Active Reproduction Test.[51] This suggests that these tests are not as sensitive to differences in proprioception compared to the Threshold Test and that the Threshold Test may be a better choice to use when looking for deficits and differences in knee proprioception.[51]

Zazulak, Hewett, Reeves, Goldberg, and Cholewicki[52] studied the proprioceptive control of the body's core and the affect it has on knee stability, with the premise that impaired control of the core would affect the dynamic control of the knee and lead to possible knee injuries. Zazulak et al.[52] wanted to determine if there are identifiable factors related to proprioception of the core that would predispose athletes to knee injuries. Therefore, the objectives of their research[52] were to determine if decreased core proprioception would increase knee injury risk and if decreased proprioception at the core could predict knee injury risk in female athletes and not in male athletes.

Subjects were placed into an apparatus that produced passive lumbar spine motion in the transverse plane.[52] This apparatus eliminated vestibular contributions to core proprioception and visual, auditory, and tactile cues from the apparatus were controlled for. Therefore, this system was designed to focus primarily on information from muscular and articular mechanoreceptors in the trunk.[52] The subjects were rotated away from neutral and were required to either actively rotate themselves back to neutral or, when passively moved toward neutral, they were required to stop the apparatus when they perceived they were at the neutral position. Subjects completed 5 trials of both passive and active tests of returning to neutral. The individuals were tested at baseline and then followed for a 3 year period to track any knee injuries.[52]

During the 3 years following baseline testing, 25 individuals out of 277 sustained knee injuries. This included 4 females and 2 males sustaining anterior cruciate ligament ruptures. The other knee injuries included other ligament or meniscal injuries.[52] Zazulak et al.[52] found that females with knee ligament/meniscal injuries had a decrease in their active proprioceptive repositioning compared to non-injured females. There were no deficits in passive proprioceptive repositioning found between injured and non-injured male and female athletes. Furthermore, there were no significant differences in active proprioceptive repositioning between injured and non-injured male athletes.[52]

This research[52] showed that decreased core proprioception is associated with an increased risk for knee injury. It was observed that a deficit in active proprioceptive repositioning of the trunk in injured female athletes supported the author's objective that deficits in core proprioception could predict knee injury risk in female athletes and not in male athletes.[52] Zazulak et al.[52] suggested that deficits in core proprioception can alter the stability of the knee and lead to an increased risk for knee injury. Furthermore, this may advise the need for core proprioception screening prior to athletic involvement.

Zazulak, Hewett, Reeves, Goldberg, and Cholewicki[53] proposed a study to identify neuromuscular factors related to core stability that would increase the likelihood of an athlete to a knee injury. Zazulak et al.[53] wanted to determine if an increased trunk displacement after sudden force release would increase an individual's risk for knee injury and if lateral angular displacement of the trunk would be the best predictor of knee injury. They[53] used logistic regression models of combined factors to predict knee injuries and also to determine whether these models differed between men and women. Core stability is thought to be the basis of trunk control and it allows for the dynamic control and transferring of force along the kinetic chain to distal extremities.[53] Therefore, if the stability of the core is disrupted, the controlled transfer of force and motion to the lower extremity may place distal segments at risk for injury.

This study[53] was limited to only healthy males and females, with no prior history of knee injuries. The subjects were tested at baseline and then were followed for 3 years to determine if they experienced any knee injuries. At baseline testing, subjects were placed in a wooden apparatus that restricted any lower extremity motion and pelvic motion. It allowed for an isometric exertion in trunk flexion, extension, and lateral bending. With the restricted lower extremity joints, this ensured that they would not contribute to any postural adjustments. A cable was attached to the back of a harness worn by each subject. The cable applied resistance for the isometric exertions. The resistance was set at 30% of maximal isometric trunk exertions for an average individual. The resistance was applied and suddenly released, with a Flock of Birds device recording trunk motion after. Angular trunk displacement was measured for 150 milliseconds after release and maximal displacement was averaged across 5 trials.[53] After analysis of these variables, the authors determined which displacement parameters were significantly different between injured and non-injured athletes. These were then used in a binary logistic regression model for predicting knee injury. Included in this analysis was the displacement data as well as active proprioceptive repositioning error of the trunk and a history of low back pain.[53] Active proprioception repositioning data was collected in the study mentioned earlier by Zazulak et al.[53]

Over the following 3 years, 25 individuals sustained knee injuries, 11 females and 14 males. Six of these injuries were ACL ruptures, consisting of four women and two men.[53] Upon analysis of the injured to non-injured statistics, both maximum displacement and angular 150 millisecond displacement were significantly greater in the injured athletes.[53] Also, ligament injured female athletes demonstrated greater maximum displacement than non-injured females. Yet, the male groups had no significant difference between injured and non-injured athletes in all measured parameters.[53] Furthermore, Zazulak et al[53] reported that the multiple logistic regression model showed that lateral, extension, and flexion displacements were the primary predictors of ACL injury with 83% sensitivity and 76% specificity. Of the three, lateral displacement was the strongest primary predictor of knee, ligament, and ACL injury in female athletes, but not male athletes.[53] When combined with active proprioception error repositioning and a history of low back pain, it was reported that both were also predictors of knee injury in female athletes; yet, the strongest predictor for knee injury in males was low back pain.[53]

Zazulak et al[53] discussed the relationship between decreased core neuromuscular control and the risk for knee injuries. Previous studies have concluded that decreased core neuromuscular control may increase the risk for valgus positioning of the knee.[54,55] Furthermore, the authors[54,55] noted that valgus positioning of the lower extremity is a contributing factor to the mechanism of ACL injury for female athletes. Hewett, Myer, Ford, et al.[54] found a decreased risk for ACL injury with female athletes when they participated in a neuromuscular training program that included core stability exercises. As a result, Zazulak et al[53] proposed that if physical therapists incorporate typical core neuromuscular training programs into training sessions for athletes, the potential to decrease knee injury risk exists.[53] The authors[53] continued to discuss their findings of increased lateral displacement of the trunk in the coronal plane as the primary predictor of knee injury in females. This supports a study by Paterno, Myer, Ford, and Hewett[56] who concluded that neuromuscular training for females should focus on the coronal plane due to valgus collapse occurring in the coronal plane. In combination with this, Zazulak et al.[53] proposed that core stability neuromuscular training should be completed in the coronal plane, since the coronal plane is associated with valgus collapse. Overall, the decreased neuromuscular control may add to the increased valgus position of the lower extremity and, therefore, core muscle training may increase control and decrease this valgus tendency.[53]

Biomechanical ACL Injury Mechanisms

Borotikar, Newcomer, Koppes and McLean[57] understood that both fatigue and decision-making independently impact injury risk to the anterior cruciate ligament, leading to their further examination of the combined effects of these variables. Decision making was defined as a subject's anticipatory demand to the anticipated or unanticipated landing task.[57] Subjects performed forward jump landing tasks while standing two-meters behind a set of force plates. Three explicit light stimuli directed subjects to land on left foot, right foot, or both feet. The light stimulus was then followed by a single-leg cutting task, or double-legged vertical jump. Anticipated trials consisted of light stimuli being given five-seconds prior to the jump phase of the single-leg tasks, while subjects in single-leg unanticipated trials were given the light stimuli immediately after initiating the jump phase.[57] Twenty-four subjects performed 30 trials pre-fatigue, followed by trials with a fatiguing protocol consisting of double-leg squats in-between each jump landing task until 100 percent fatigue was reached.[57] As expected, fatigue paired with unanticipated tasks had significant interaction effects upon initial contact for decreased hip flexion and increased hip internal rotation, compared to anticipated landings.[57] Borotikar et al[57] postulated that fatigue of the hip and knee extensors limit the ability to eccentrically control flexion; thus, landing in a more extended position may prevent excessive collapse from occurring. Intuitively, the gluteals secondary control of internal rotation would be compromised in the presence of a fatigued state. Furthermore, the study revealed that peak stance knee abduction increased significantly and knee internal rotation trended toward increases with combined conditions of fatigue and unanticipated landings.[57] These motions are known to increase load on the ACL, and may be predictive of ACL injury.[57,58,59,60] A discussion of these risky motions suggests that exhaustion from the fatigue protocol may compromise ligamentous proprioception by inhibiting ligament mechanoreceptor feedback, and leading to out-of-plane knee joint posture.[57,58,59,60] This posture, with hip internal rotation and knee abduction, compromises the optimal length of the quadriceps and hamstrings and decreases the ability to further control knee abduction.[57]

To determine gender differences in lower extremity landing mechanics post-fatigue, Kernozek, Turry, and Iwasaki[61] used a drop landing technique where subjects dropped from a stable hanging bar. Two sets of six drop landing trials from the bar, which was adjusted so that each subject's feet were 50 centimeters from the floor, were performed by dropping onto a force platform with the dominant leg. The first set was performed prior to a fatigue protocol, while the second set immediately followed a fatiguing exercise of squats until weight could no longer be lifted.[61] Kernozek, et al[61] decided to study single-legged landing because of asymmetries often observed between legs in double-legged landings, and because most ACL injuries are associated with single-legged landings.[61]

Women were observed to have significantly higher vertical ground reaction forces (VGRF) than men both pre- and post-fatigue.[61] Pre-fatigue, women landed with 14 percent greater hip flexion angles, while post-fatigue, both genders landed with respectively greater hip flexion angles, with women showing 34 percent greater hip flexion than men.[61] The study[61] revealed that men utilized significantly greater maximum knee flexion than women did post-fatigue. Across pre- and post-fatigue trials, men also exhibited larger peak varus knee angles, whereas women had larger peak valgus knee angles across trials.[61] Greater valgus angles have been associated with ACL injury risk,[61] and these results suggest that women are at higher risk than men regardless of fatigue. Both genders acted similarly at the ankle; increasing dorsiflexion with fatigue.[61]

Kernozek et al[61] also reported significant decreases in hip and knee compression across genders, post-fatigue. Though both genders utilized a landing style post-fatigue that decreased anterior shear force, men were able to successfully reduce their shear force by 38 percent, while women only reduced theirs by 20 percent.[61] Both genders similarly reduced their hip extensor moment (by landing with greater hip flexion), knee extensor moment (by landing with greater knee flexion) and knee varus moment (by landing with greater knee valgus), while increasing their ankle dorsiflexion on landings after neuromuscular fatigue.[61]

The differences in landing styles that were revealed in the study[61] allowed men to decrease their vertical ground reaction force. Post-fatigue, men were also better able than women to adopt a landing style to reduce the anterior shear knee joint force. Women's adaptation of landing with larger valgus angles, less knee flexion, and greater hip flexion may be the reason for this discrepancy in change of knee anterior shear force post-fatigue.[61] These characteristics of valgus loading, increased shear force, and greater knee extension resemble proposed non-contact injury mechanisms to the ACL. Thus, these characteristics suggest women are more susceptible to ACL rupture.[61] It is postulated that increasing dorsiflexion in both genders is one way to absorb ground reaction force and remove some of the energy that would otherwise be compensated at the knee. This adaptation may decrease the risk of an ACL injury.[61]

In addition to risk of ACL injury, the resulting neuromuscular control and biomechanical performance is also a point of interest following anterior cruciate ligament reconstruction. Vairo, Myers, Sell, Fu, Harner, and Lephart[62] studied the effect that anterior cruciate ligament reconstruction (ACLR) has on neuromuscular and biomechanical performance, and their resultant ability to restrict anterior tibial shear forces (ATSFs). Reconstructions using ipsilateral semitendinosus and gracilis autografts (ISGA) were specifically observed for the purpose of determining any significant neuromuscular or biomechanical deficiencies due to injury inflicted on its harvesting site.[62] Fourteen recreational athletes with ISGA approximately two years post-ACLR were matched against 14 healthy controls and performed single-leg vertical drop landings (VDL). In order to gather data, subjects stood on one leg upon a 30 cm high platform and stepped off, landing on a force plate with the same one leg.[62] This force plate then calculated moments, angles, and VGRF.

Though, no differences were found in hip and net summated extensor moments, subjects with the ISGA, ACLR did land on their involved leg with decreased peak VGRF than their uninvolved and the matched control.[62] This decreased VGRF is consistent with the increased peak hip, knee, and ankle joint flexion angles reported upon landing on the involved lower extremity. These increased angles serve to soften the landing imposed on the involved leg and may be an adaptation to protect the knee joint and ACL from injury recurrence.[62]

Surface electromyography (SEMG) results indicated significant increases in the reactive muscle activation of vastus medialis, vastus lateralis and medial hamstrings of the involved leg compared to matched controls.[62] Additionally, decreased preparatory and reactive muscle activation of the medial gastrocnemius compared to the uninvolved internal control leg was also revealed.[62] Though the gastrocnemius usually plays a role in creating an internal knee flexion moment, which would shield the ACL from injury, it also can serve to antagonize the ACL by pulling the femur posteriorly on tibia. A quiet gastrocnemius, then, would serve as an adaptation to lessen antagonistic affects on the ACL.[62] Finally, greater preparatory and reactive co-contraction activity of the quadriceps and hamstring were found on the ACLR leg compared to the matched control. This mechanism may be a strategy to reduce ATSF's, tibial rotation and subsequent loads imposed on the ACL when landing.[62]

In the same study,[62] separate strength and endurance testing using a dynamometer showed no difference between internal and matched controls for hamstring performance. This is contrary to the authors'[62] hypothesis that damage to the hamstrings by harvesting the semitendinosus and gracilis autograft would result in decreased hamstring strength; contributing to increased ATSFs. It is tangible that, since all subjects with ACLR in this study had undergone sports rehabilitation focused on hamstring musculature, these results were confounded and may not be generalizable. Alternatively, these results may support an indication that hamstring strengthening may be vital in providing the synergistic support the hamstrings deliver in supporting the ACL by dampening peak VGRFs and controlling ATSFs.[62] Despite showing no strength or endurance deficits, subjects with ISGA ACLR exhibited strategies of kinetic, kinematic, and muscle activation that were uncommon to healthy controls.[62]

Rudolph, Axe and Snyder-Mackler[63] studied dynamic stability mechanisms following ACL reconstruction in copers and non-copers. Eleven copers were defined as ACL deficient for at least one year with no instances of knee instability during participation in high level sports. Ten non-copers, to the contrary, were ACL deficient within eight months of rupture, with knee instability during activities of daily living. Additionally, ten uninjured subjects were matched to the coping group.[63] Each subject was asked to perform five trials per leg of hopping onto and immediately off of a force platform. However, six of the ten non-copers opted to not participate in the hopping trials, based on fear that they would reinjure their knees. Thus, statistical evidence could not be used for comparison due to such a small sample size.[63]

Hop quotient, which was calculated by the equation [(involved hop length/uninvolved hop length) X 100%], was no different between copers and uninjured subjects.[63] Of the few differences between copers and uninjured subjects, copers had lower external hip flexion moments in both legs than did uninjured subjects at the transition to hop propulsion.[63] Also, the summated internal moment created by the hip, knee and ankle showed significant increased support from the ankle. Minimal kinematic and kinetic differences led to no difference in VGRF observations between these two groups. EMG data collected concomitantly during hopping showed differences in muscle patterns used, suggesting that copers used different muscle activation strategies than uninjured subjects.[63] Hop quotient in uninjured subjects significantly correlated to knee moment at peak knee flexion, which was statistically accounted for by increased EMG activity of the medial gastrocnemius at initial contact, and vastus lateralis and medial gastrocnemius co-contraction.[63] Alternatively, the copers' strategy preferred increased EMG activity of the soleus muscle at initial contact and an external hip flexion moment at peak knee extension. This observation that copers assumed a more extended hip, knee, and ankle position at the transition to hop propulsion may be accounted for by the ankle plantar flexors, specifically the soleus, contributing to knee stability by limiting anterior tibial translation with knee flexion.[63] Transferring knee stability to the ankle allowed copers to achieve normal hop symmetry when compared to uninjured subjects who absorbed more forces at the knee.[63]

Cowley, Ford, Myer, Kernozek and Hewett[64] examined the differences in ACL injury mechanisms for female basketball and soccer players. Fifteen female basketball players and fifteen female soccer players were asked to perform three drop vertical jumps consisting of stepping off of a box, landing bilaterally on to two force plates and immediately jumping.[64] This task served to act as a similar movement performed in a basketball game. As hypothesized, the basketball players landed with greater peak GRF than did soccer players. Additionally, stance time was significantly shorter in the basketball group.[64]

A second task, this time soccer specific, was performed by jumping forward and landing bilaterally on the force plates, then immediately performing a 45 degree cutting maneuver to the left or right. Three trials in both directions were performed by both groups with a light cue randomized for either direction.[64] Again, the authors' hypothesis that soccer players would show greater peak GRF than would basketball players was supported in this task. Stance time was also significantly shorter for the soccer group in this cutting maneuver.[64]

In this study,[64] groups did not statistically differ from one another in knee valgus during either maneuver. However, knee valgus angles were 27.7% greater during cutting maneuver, than the drop vertical jump. Significant differences were found between subjects' legs, too, with greater valgus moments on the dominant leg during the cutting maneuver.[64] Of interest, the cutting maneuver showed greater peak GRF on the dominant leg, whereas the opposite was found true for the DVJ.[64] This finding implies that different tasks may partial to different legs.

The most common method of injury for a female basketball player is during a jumping or landing movement.[64] For soccer players, the method is during a cutting maneuver.[64] One argument for these injury methods is that these movements are more common in these respective sports, thus will be the common method for injury. Additionally, greater force applied over a shorter period of time also has implications of higher risk for ACL injury.[65] Since female basketball players have adapted to the mechanism of their sport by becoming faster and stronger at jumping maneuvers, they put themselves at increased risk for injury during this method. The same can be said for soccer players becoming faster and stronger at cutting; suggesting a higher risk for ACL injury during these tasks.[64] Much of this may also be due to the increased valgus angles during cutting. Increased valgus may be the result of inability of musculature to absorb GRF and subsequently transferring that load to the ligaments of the knee.[19] It is not surprising, then, that increased valgus values during the cutting maneuver were found on the dominant leg, which had greater GRF over a shorter period of time.[64] Either way, these authors' findings present insight that the mode of injury for an athlete may be specific to the sport they play.

Paterno, Ford, Myer, Heyl, and Hewitt[66] studied limb asymmetries in females returning to sports following ACLR. Fourteen female athletes 27.4±13.8 months post-ACLR were matched with 18 healthy female athletes and were asked to perform 3 DVJs by dropping off of a box, landing with both feet on a force plate and immediately jumping as high as possible.[66] During landing, the involved leg of the ACLR group showed no difference in VGRF than either leg of the control group. However, the uninvolved limb had significantly greater VGRF across limbs. Upon take-off, the uninvolved leg did not differ from either control leg in VGRF, whereas the ACL reconstructed limb showed significantly less VGRF. Loading rates showed that the involved leg significantly accepted force over a longer period of time, when landing, than the uninvolved and control limbs.[66] As, hypothesized, subjects with healthy knees showed no asymmetries between legs during a DVJ task, while ACLR subjects showed the contrary. Interestingly, these asymmetries were still evident at 27 months post-surgery and may continue to pose increased risk of injury to the contralateral limb.[66]

Asymmetries may be a compensatory mechanism to protect the involved knee from recurrence of injury, or as a result of weakness of the involved limb. The healthy limb may accept more burden to continue to accomplish certain tasks. Greater GRF over a shorter period of time has been implicated in injury risk.[60,65,67]

Vision and its Influence

Vision is thought to be a vital sense for people to complete many tasks. Liebermann and Goodman[68] produced a study that looked at vision and its ability to dissipate vertical ground reaction forces when landing from varying heights. Their research[68] entailed a randomized study of six males with a mean age of 26 years, mean height of 177.83cm, and a mean body mass of 76.66 kg. The six males were randomly assigned to either participate in the vision or no-vision group first, with the second testing to follow after 2-4 days rest. In the no-vision trials, the participant was allowed to visually see the environment, so that he knew the height he was falling from. To restrict vision, the participants then put on dark goggles to eliminate all visual cues. Each participant completed six blocked landings for each height range (5-10, 20-25, 60-65, and 90-95cm) for both with vision and with no vision conditions for a total of 48 landing trials.[68] Both groups were instructed to hang motionless onto a steel bar that was oriented horizontally. The bar was raised to varying heights and participants were to release their hands and drop vertically down onto a force plate below, which was covered in a rubber foam pad to decrease pain of landing on metal with bare feet.[68] When landing, the participants were instructed to land “almost noiseless” and to prevent sudden deep knee flexion. The steel bar had an electronic switch that allowed a microcomputer to detect time of release from the bar. The force plate measured the ground reaction forces during the landing. These forces were split up into four components: amplitudes of the first peak (first sudden increase), second peak (major peak after touchdown), and the respective times to first and second peak (measured form the moment of contact to each peak).[68]

Two-way repeated ANOVAs were used to analyze the data to find what, if any, correlation existed between vision or no-vision and the forces created at the four height intervals. A significant main effect of higher mean amplitudes (3.44 and 2.95 times body mass, $p> 0.05$) was found during the first peak with vision for the 60-65cm and 90-95cm landing heights.[68] This shows a greater initial peak force with vision compared to no-vision. Liebermann and Goodman,[68] speculate that this finding is due to participants’ over-reliance on vision.[68] When vision was taken away, the participants may have prepared for initial impact before touching the force plate, allowing their muscles to decelerate the body more effectively and prevent the hard or forceful impact.[68] The time to first peak for both the vision and no-vision groups was found to have non-significant main effects meaning there was not a difference between the groups; in both conditions participants were able to elicit the first peak amplitude in similar time frames.[68] The amplitude of the second peak and the time to second peak did not have a main effect for either the vision or no-vision conditions.[68] This reinforces that there is little difference in the landing forces with or without vision.

Participants in this study[68] did not produce landings in the absence of vision that had higher ground forces compared to when using vision. Actually, the landings without vision had equal or less amplitude of force as detected by a force plate. Liebermann and Goodman[68] note that this could be due to not overly relying on vision and thus initiating a muscle tension to soften the landing sooner. Also, it was stated that since the participants had visual knowledge of the environment before the drop happened, they may have used other processes to compensate for continuous visual input, such as temporal estimation of when the landing event would happen after the drop was initiated.[68] The conclusion of the study was that when the environment is known, vision is not necessary to adopt appropriate landing strategies; in fact, vision may possibly even hinder initial impact slightly.[68]

Thompson and McKinley[69] designed a study to determine the relationship between vision and muscle activity for preparation of a landing by perturbing vision through disrupting the velocity component, eliminating vision, and putting vision and vestibular senses in conflict. Eight physically active females, ages 20-30, with no neurological disorders were used in this study. They had to jump off of an adjustable platform and land in a 0.6m² target zone, 0.3m in front of the platform without taking a step forward.[69] Each subject partook in two sessions. The first session consisted of 40 jumps from a height of 0.45m with vision not disturbed. A strobe light used to disrupt the velocity component and vision was obstructed with blackened goggles. A visual dome was used to put vision and vestibular senses in conflict.[69] The second session was after a 10 minute break and consisted of 36 jumps from randomized heights of 0.35m, 0.45m, and 0.55m (in addition to randomizing the order of the four conditions of vision used in session one).[69] To measure the anticipatory muscle reactions that occurred with the different conditions, surface EMG was collected from the right leg on the rectus femoris, biceps femoris, tibialis anterior, and the lateral gastrocnemius.

Using a two-way ANOVA, it was found that during the first session the muscle onset latencies were all significantly different from each other and always followed a distal to proximal progression with all visual conditions.[69] The lateral gastrocnemius initiated first at -132ms, the tibialis anterior at -80ms, the rectus femoris at -51ms, and biceps femoris last at -8ms.[69] The stability of the sequence throughout heights and visual perturbations suggests that vision is not a significant contributor to the sequencing of muscle activation in anticipation of landing from a jump.

A few general trends were noted with this research.[69] First, the lateral gastrocnemius was initiated closer to landing with visual perturbations, regardless of jump height. With visual perturbations, the tibialis anterior and rectus femoris onset latencies were closer to the landing when the heights were lower. There was greater overall instability with randomization with the conditions, with a 30% rate of participants stepping after the landing.[69] Thompson and McKinley[69] suggest that predictability is important and is the reason these trends appear when the conditions are randomized. Without vision or consistency in height, a global default strategy may be used to anticipate landing leading to onset latency changes of the muscles becoming closer to the landing. Overall, the sequence of muscle activation in preparation for landing is very stable and unaltered by varied heights or visual perturbations; however, onset latencies may be altered with randomized heights and visual perturbations through use of different strategies.[69]

Liebermann and Goodman[70] investigated whether or not continuous vision is used during free-fall events when subjects are aware of their surroundings from previous knowledge. In order to perform the research, six injury-free, volunteer subjects completed six randomized sets of six different trials for a total of 36 free-fall landings. In addition to the trials being randomized, conditions were also manipulated by utilizing normal vision or a blindfold in complete randomization as well.[70] Prior to the initiation of the testing, EMG electrodes were placed on the muscle belly of the gastrocnemius, tibialis anterior, biceps femoris, and rectus femoris on the subjects' left leg; the electrodes were used to determine the muscle activity during the landing mechanism.[70] In each trial, patients held on to a horizontal bar that was attached to both the ceiling and the ground and was then suspended until the subjects' forefoot lost contact with the floor. Patients were instructed to hang in a still position (without movement) from the bar while staring straight ahead at a black strip placed 40 cm ahead. If the patients were blindfolded for a particular trial, they were instructed to complete the same procedure. During the testing trials, subjects were elevated to 15, 45, or 75 cm, depending on randomization. Patients were then instructed to perform a vertical descent, landing on bilateral lower extremities on a Kistler platform which was used to measure the vertical ground reaction forces that occurred at landing.[70] In addition to measuring ground reaction forces at landing, joint kinematics were also assessed using a polarized-light goniometer which was projected through the sagittal plane of the participant. Polarized-light goniometer sensors were placed on the forefoot, external malleolus, and distal end of thigh. Joint kinematics were assessed both during the descent and after landing at the left hip, knee, and ankle joints.[70]

In order to assess the effects of vision, the authors[70] measured time to contact T_c from the EMG data in order to determine the moment of landing. To measure time of contact while taking the blindfolding condition into consideration, the authors[70] chose to measure the onset time relative to the moment of release, L_o. In addition, while analyzing the GRF of landing, F_{max} was used to measure peak vertical force associated with voluntary landing actions and T_{max} was used to assess the time taken to reach the peak force. Lastly, normalized impulse, I_{norm}, was also utilized as an additional way to compare between subjects with different body masses, the magnitude of impact at landing.[70]

Results from the research[70] show that both L_o and T_c follow a linear trend, despite if vision was available or not. It was found that in both the vision and blindfolded trials, T_C of the gastrocnemius and rectus femoris increased, meaning that vision was used whether the subject was blindfolded or not (Gastrocnemius=ρ=0.711 vision, ρ=0.673 blindfolded) (Rectus Femoris=ρ=0.832 vision, ρ=0.837 blindfolded).[70] It was expected that with vision occluded, T_C would increase at a faster rate than if vision was available in order to initiate activation upon descent as a protection mechanism. Likewise, it was thought that initiating action would occur later in both visual conditions, particularly the blindfolded condition, based on the increased height of the bar; this delay in initiation would cause L_O to follow a linear regression. The results revealed, however, that L_O of the rectus femoris and gastrocnemius did not continuously occur at a later time as the drop height increased (Gastrocnemius=ρ=0.934 vision, ρ=0.891 blindfold) (Rectus Femoris=ρ=0.940 vision, ρ=0.922 blindfold).[70] These results show that whether or not vision is available to prepare a subject for landing, the actions taken to prepare are very similar.[70] These results were further analyzed by assessing the ground reaction force data that was calculated upon landing.[70] Again, it was hypothesized by the authors[70] that dropping while blindfolded would result in a decreased ability to reduce the impact forces at landing when compared to acting without vision impaired. After analyzing F_{max}, T_{max}, and I_{norm}, it was found that there were no significant differences in the ability to reduce impact forces if vision was taken away (F_{max}=p=0.6576, T_{max}=p=0.5505, and I_{norm}=p=0.2592).[70] This research provides evidence to support the thought that being familiar with one's surroundings prior to falling may help to reduce the need for vision to prevent major injuries while falling.[70]

Kahn and Franks[71] proposed a study to look at the effects of visual feedback on initial impulse and error correction. Previous researchers have proposed that movements are made up of two phases, an initial impulse and an error correction phase.[72,73] Furthermore, initial impulse is defined as a fairly rapid, continuous change in the position of the limb. Error corrections are characterized by discontinuities in kinematic profiles that are said to reflect the presence of discrete on-line adjustments.[71]

Sixteen male and female right-hand dominant university students participated in this study. The arm and hand were hidden from the subjects' view by an opaque shield. In this position, the elbow could rotate freely in the horizontal plane. This would be the movement that would move the cursor. The subjects' were given visual displays in front of them on an oscilloscope screen. The screen displayed the home position, target region and cursor symbolizing their limb position. The target was located 9cm to the right of the home position. Knowledge of results was given regarding accuracy and movement time on the monitor. At the beginning of each trial, the subject was asked to move the cursor to the home position. Once there, a tone was presented indicating the participant to move their cursor from the home position to the target position as quickly and accurately as possible.[71]

The subjects were randomized into two groups of eight. The full vision (FV) group practiced the aiming task with vision of the cursor while the no vision (NV) group practiced under a situation where the cursor disappeared after the initial movement away from home position. Participants in each group performed 1,500 trials over five sessions.[71]

This study[71] found that participants increased the accuracy of their movements with practice while decreasing the time to move. Furthermore, the present study[71] showed that the effects of practice varied greatly between the two feedback conditions. The FV feedback group was more accurate than the NV feedback group, while the movement times decreased for both groups with practice. Kahn and Franks[71] reported that in past research, FV and NV conditions were found to have greater accuracy with longer movement times. They credited this to reflect the cost of the time to make visual error corrections.[74] The present study[71] was interested in what occurred during practice to allow this change to occur. Kahn and Franks[71] found that the initial impulse and error correction phases contributed to this higher level of accuracy with decreased movement time. Participants who practiced with FV feedback had less variability in the location of the initial impulse. Furthermore, those who practiced with FV spent less time in the initial impulse phase as a result of practice, while those in the NV group held their initial impulse movements relatively constant.[71]

In addition, Kahn and Franks[71] found that removal of visual feedback had a negative effect on accuracy. This removal of visual feedback affected both initial impulse and error correction phases. Kahn and Franks[71] reported that this may be due to the specificity of practice hypothesis that different sources of sensory information are combined so that a sensiomotor representation of a movement pattern is formed.[75] When one sensory afferent is removed from this information, the performance of that given movement will decrease due to no longer having that sensory input. Proteau, Tremblay and DeJaeger[76] further proposed that with practice, afferent information that meets the demands of the task will dominate other sensory information. Removal of this leading sensory afferent will result in deterioration of movement if that dominance has been established.[76] In summary, this article[71] showed that visual feedback had a major role in determining how an individual will alter their movement strategies. When vision was available, subjects relied on the visual information and used it to make their movement faster and more accurate. When visual information was not available, participants focused on reducing the need for error correction.[71]

Santello[77] performed a review to summarize the motor control mechanisms that account for impact absorption from falls. The reviewer[77] proposes that preparatory muscle activation occurs during the airborne phase, prior to landing. This may be a strategy to prepare the muscle-tendon complex for impact absorption and is anticipated by the central nervous system. The degree to which one activates muscle force prior to landing determines the level of muscle stiffness, which Santello[77] postulates will modulate muscle spindle sensitivity or reflex muscle activation throughout the muscle-tendon complex, upon landing. Multiple studies support this by examining pre-landing EMG amplitude as a function of drop height. This is supported by additional studies comparing unexpected falls to self-initiated falls. During an unexpected fall, there seem to be two preparatory EMG responses purportedly initiated first by otolith afferents and second by visual afferents. Height change does not appear to affect the modulation of preparatory muscle activation during unexpected falls. Self-initiated falls, however only have the visual EMG response, wherein amplitude response seems to be directly related to drop height. The inability to correctly modulate muscle stiffness relative to drop height may account for larger ground reaction forces reported in unexpected falls.[77]

Two other ways that preparatory muscle activity may be modulated is by duration of pre-landing muscle activity and muscle activity latency, or the time between take-off and preparatory response.[77] It is suggested that the time between take-off and initiation of pre-landing EMG is directly related to height; greater height means greater delay in preparatory muscle activity.[77] To the contrary, duration of preparatory muscle activation is relatively constant regardless of height and may not be related to the time of take-off. Hence, the central nervous system may be timing the initiation of muscle activity relative to foot contact.[77]

Evidence[77] also suggests that regardless of drop height, persons tend to drop with an extended position relative to segmental orientation. Santello[77] discusses that this may allow absorption through the entire range of motion of the lower extremity segments. After touch-down, muscle force is required to slow down and stabilize body posture. Studies of subjects performing drop landings through a paper thin false landing supports the idea that reflex mechanisms and central nervous system both contribute to touch-down muscle activity for posture stabilization. The studies showed that there was EMG activity when contacting the false platform (CNS), but significantly more EMG activity during the ankle stretch (reflex) producing contact of the solid platform.[77] Santello[77] continued to review the effect of vision on ground reaction force. It seems that even drop height information, without continuous vision throughout the drop may be enough information to land with adequate ground reaction force. In a study where subjects were allowed to view the drop height before initiating the fall, they landed with similar ground reaction forces to those who had continuous visual information during the fall.[77]

Vestibular and proprioceptive information may also contribute when vision is lacking. When subjects repeatedly dropped from the same height without vision, they were able to compensate with evidence of EMG timing and duration similar to that of subjects with vision.[77] However, vestibular and proprioception did not seem to be enough for compensation of joint rotation at foot contact, as ground reaction forces were highly variable.[77]

CHAPTER III

METHODS

Subjects

Thirty-four female volunteer subjects between the ages of 18 and 45 years (mean 25.9 ± 6 years) were recruited for this study from the University of Minnesota and Twin Cities metropolitan athletic performance training centers. This study consisted of 17 subjects with unilateral ACL reconstructions and 17 control subjects with no recent history of knee problems. All subjects completed an informed consent form which was approved by the Institutional Review Board at the University of Minnesota. In addition to informed consent, all participants also signed the University of Minnesota Academic Health Center's Authorization for Photography, Filming, or Interviewing because all trials were videotaped and linked to the Motion Monitor system for review and data reduction.

Participants were asked to report demographic information including age, self-reported height, bodyweight, type of ACL reconstructive surgery, and date of surgery which is presented in Table 3.1. To determine eligibility, subjects were required to complete a KT-1000 test to determine bilateral anterior laxity and limb symmetry hop tests. This information was gathered using the subject data collection form with successful and unsuccessful trials also being documented. If subjects were deemed physically fit to participate in the study, each subject then filled out the remainder of the Cincinnati Knee Rating Scale (hop functional testing and clinical examination are part of the CKRS)[78]. This additional descriptive data on the ACL subjects is presented in Table 3.2. The Cincinnati Knee Rating Scale was used to gather additional information on the subject's ability to function,[79] but the radiographic portion of the CKRS was not included in this study due to the lack of available x-rays from subjects. This rating scale has been found to be reliable, valid, responsive, and acceptable for clinical research.[80] Overall, the ACL subjects self-reported function as high. ACL subjects described mostly normal/unlimited activity levels (12/15) and a patient grade of 8.4/10, indicating good to excellent overall knee ratings at the time of testing.

Table 3.1. Demographic Data for Healthy Subjects (n=17) and ACL Subjects (n=17).

Variables	***Healthy Mean Values (SD)***	***ACL Mean Values (SD)***
Age (yrs)	25.3 (6.0)	26.5 (6.3)
Height (in)	66.3 (2.4)	66.8 (2.9)
Weight (lbs)	131.4 (12.6)	145.4 (14.2)*
KT Change	0.90 (0.74)	1.70 (0.97)*
Cut length	0.38 (0.07)	0.36 (0.08)
ACL reconstructed limb	NA	Left (13) Right (4)
Type of Surgery**	NA	PT (9) HS (7) Cadaver (1)
Limb Dominance	Right (16) Left (1)	Right (17)

* denotes statistically significant difference from healthy subjects.

**PT = patellar tendon, HS = Hamstring

Table 3.2. Descriptive Data for ACL Subjects (n=17)

Variables	***ACL Mean Values (SD)***
Years post surgery	4.6 (2.7)
Limb Symmetry Triple Hop (% of uninjured)	95.8 (8.3)
Limb Symmetry Crossover Hop (% of uninjured)	97.2 (10.8)
CKRS (Subjective)	15.9 (3.4)/20
CKRS (Activity)	12.1 (2.0)/15
CKRS (Exam)	24.8 (0.53)/25
CKRS (Instability)	19.7 (1.0)/20
CKRS (Functional)	9.8 (0.73)/10
CKRS (Patient Grade)	8.4 (1.4)/10
CKRS (Sports Activity Scale)	82.4 (15.6)/100
CKRS (Occupational Rating Scale)	33.4 (18.5)/100

Inclusion and Exclusion Criteria

ACL subjects were included in the study if they met the following criteria: (a) diagnosis of complete ACL rupture, with no severe or complex meniscus or collateral ligament damage; (b) subsequent ACL reconstruction; (c) women age 18-45; (d) no history of visual, vestibular, or neurological problems; (e) no knee pain or effusion at the time of measurement (within 2 cm is acceptable);[81] and (f) successful completion of functional tests to ensure they could complete the required experimental task (85% or greater mean limb symmetry). Functional tests which were measured included a one-legged triple hop test for distance and a one-legged crossover hop for distance.[82] Use of these two tests together has been recommended to confirm lower limb limitations.[82] Individually, each test cannot be used alone given low sensitivity scores.[82] ACL subjects were excluded from the study if they met any of the following criteria: (a) previous or current history of injury to either lower extremity (other than ACL injury) with continued dysfunction; (b) vestibular, visual, and/or neurological dysfunction; (c) bilateral ACL reconstruction; (d) or back pain that necessitated physician attendance. Healthy subjects had no history of vestibular, visual, or neurological problems, and no recent or present lower limb injuries, or back pain that necessitated physician attendance.[82]

To assist in further determination of inclusion/exclusion criteria, each ACL reconstructed subject was asked height, weight, date of surgery and type of surgery, assuring that every participant met the specific guidelines for each category. Due to the fact that the CKRS included an examination for effusion, range of motion, crepitus, and instability (including the KT-1000 test), each subject's knee was visually inspected by the Primary Investigator (PI) for swelling and scar placement for further collaboration of the type of surgery stated by the subject. Subjects were also evaluated for range of motion, tibiofemoral/patellofemoral crepitus, and for instability using the pivot shift test and the KT-1000 test. When lack of knee flexion or extension was noted, the deficit was further measured using a goniometer. Results were captured on each subject's CKRS rating form. Only one potential subject was excluded because she had bilateral ACL reconstructive surgeries and had failed to mention this during the initial phone call, stating it was an old surgery she had forgotten about. All other subjects met all inclusion criteria and therefore were not excluded from further participation in the study. The ACL laxity data collected by the PI using the KT-1000 at 30 pounds of force was collected for comparison purposes between groups.[83] The PI was a physical therapist with several years of experience using the device. Results of arthrometer measurements are commonly grouped according to a scoring system based on laxity.[84] Displacement of 6 mm or greater would indicate abnormal laxity.[84] Other researchers, however, indicate that side to side, rather than between groups differences are more accurate.[85-91] Daniel et al. reported that normal subjects had a maximum difference between the left and right side of 2 mm.[85] Researchers have suggested that an anterior side-to-side difference of 3 mm or more between the injured and uninjured knee is indicative of an ACL rupture.[87.88,92,93,94,95,96,97,98.]

Aside from the normal and ACL ruptured anterior laxity measurements, post-ACL reconstruction side-to-side differences are not well established, although researchers suggest a 5 mm difference or greater should be considered a procedural failure.[99,100] Tyler et al. suggested that side-to-side KT-1000 measurements should not be used in isolation to determine surgical failure, as scores are not associated with other clinical measures of ACL instability. [90] Reported values for sensitivity and specificity of the KT-1000 are above 89% for both.[101,95,84] Robnett, Riddle, and Kues report that clinicians can be 95% confident that changes in anterior tibial displacement of patients with ACL reconstructions greater than 5 mm with 15, 20 or 30 pounds of force do indicate a true change in tibial displacement. [102] Others report the KT-1000 test to be valid and reliable.[93,92,103,104,105,106,107,108,109,110,91] All of the ACL subjects in this study had less than a 3 mm difference between their ACL reconstructed knee and their healthy knee.

Instrumentation

Three-dimensional lower extremity kinematic data was collected using The Motion Monitor integrated system (Innovative Sports Training, Inc., Chicago, IL) with Ascension's Flock of Birds electromagnetic motion capture system (Ascension Technology Corporation, Burlington, VT). Standard size sensors measuring 1" x 1" x 0.8" were placed over the posterior head, sacrum, and bilateral femur and tibia. Sensors of this size permit precise placement over the bony segments to be analyzed. Each sensor has an orthogonal axis system embedded within it and is capable of an independent sampling rate of 100 Hz. The Flock of Birds system has a reported static positional accuracy of 0.3 inch root-mean-square (RMS) within a five foot range from the transmitter and 0.6 inch RMS within a 10 foot range. Static angular accuracy is 0.5° RMS within a five foot range and 1.0° RMS within 10 feet (Ascension Technology Corporation, Burlington, VT). A Bertec force plate (Bertec Corporation, Columbus, OH) was linked to the Motion Monitor system through an A/D interface panel (Measurement Computing's PCIM 1602 – 16 bit PCI board) for measurement of ground reaction forces (GRF). A T-BNC adaptor allowed another connection to an A/D board (National Instruments Corporation, Austin, TX) to trigger the shutter glasses mechanism. Processing of kinematic and kinetic data was performed by The Motion Monitor software (Innovative Sports Training, Inc., Chicago, IL).

The A/D board (National Instruments Corporation, Austin, TX) connected to the Motion Monitor system's A/D interface panel (Measurement Computing's PCIM 1602 – 16 bit PCI board) for GRF input also had a connection to a wireless system for the shutter glasses (Durfee Designs, Minneapolis, MN/VRex, Hawthorne, NY) to pick up the voltage drop when the glasses shuttered down. These shutter glasses allowed full vision in the open position, but were capable of being triggered at pre-selected phases of movement (based on force plate data) to shut down and block vision from anywhere between 0.1 – 2.0 seconds by a LabVIEW program set up on a laptop computer that was also connected to the external A/D board via a PCI card. Percentage of bodyweight to trigger vision disruption (*z* direction GRF data) and duration of vision disruption were adjustable parameters available on this program. The high or low tone indicating which direction the subject needed to cut was supplied by an additional laptop. This computer was linked to the Motion Monitor system to allow for data capture of the sound impulse. Figure 3.1 displays a visual description of the instrumentation set up.

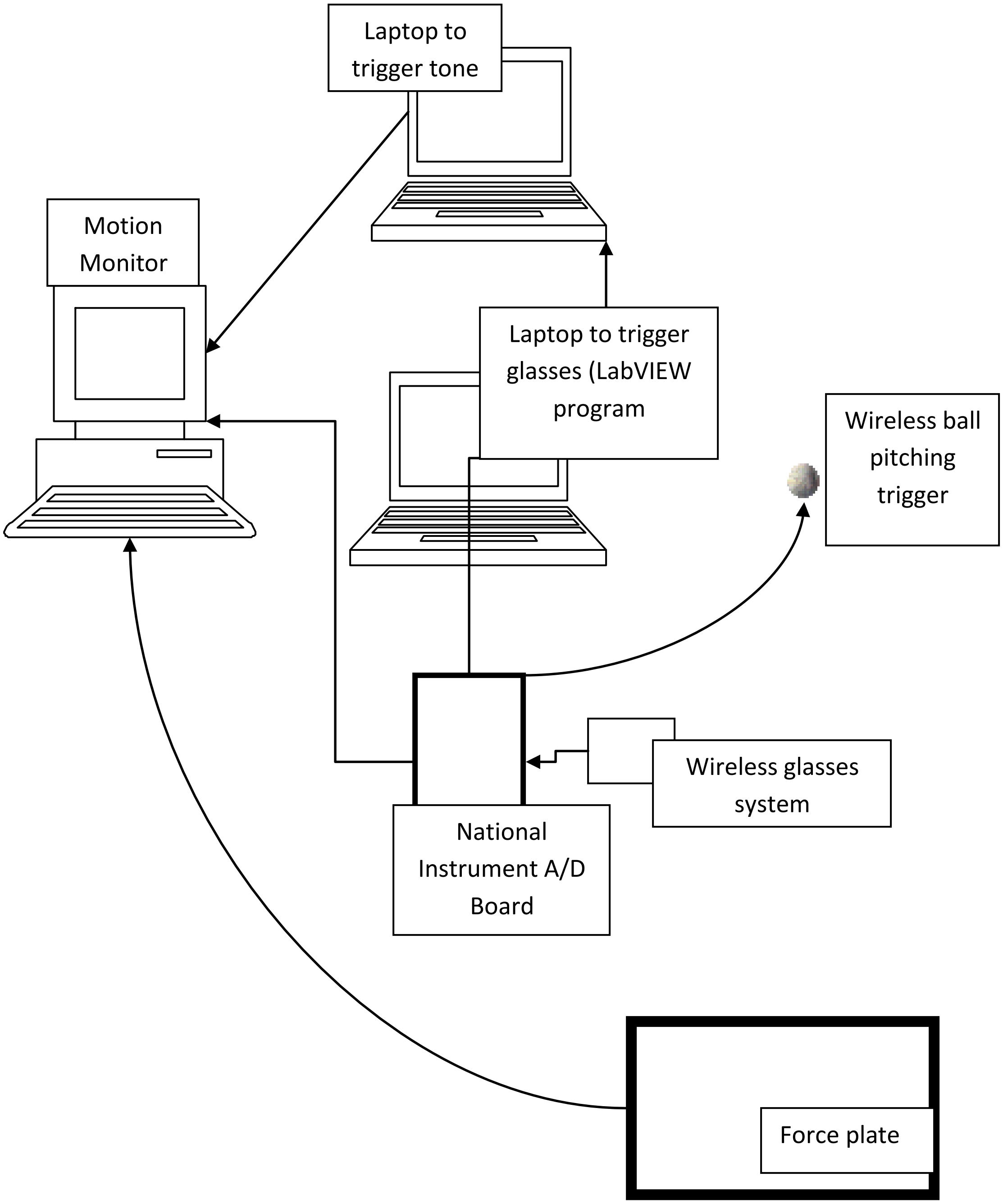

Figure 3.1. Instrumentation set up

Procedures

Leg dominance was determined by asking each subject to pretend to kick a ball. The leg the subject selected was assigned as the dominant leg for the remainder of the study.

Kinematic Assessment

Kinematic assessment was completed using the Motion Monitor integrated system (Innovative Sports Training, Inc., Chicago, IL) with Ascension's Position Capture Technology, electromagnetic sensors were attached to the skin with double-sided adhesive tape to both the posterior head via attachment to a thermoplastic molded headband and at sacral level two. Initially, the headband sensor was attached to the stylus that was used for digitization of bony landmarks. Also, sensors were attached to the mid shank of each tibia and four sensors to each distal lateral thigh near the iliotibial band (ITB) in order to avoid excessive movement. These sensors were secured with athletic pre-wrap and tape or Velcro straps.

International Society of Biomechanics (ISB) recommendations for the hip and ankle and Grood and Suntay recommendations for the knee were used to capture lower extremity movement by digitizing anatomic bony landmarks on the pelvis, thigh, and shank.[111, 112,113] To determine the location of the hip joint centers, the Leardini method was used.[114] Because the Motion Monitor system is unable to convert hip joint center data to the anatomical coordinate system set up when capturing points for the anatomical coordinate system, the greater trochanter was then used to capture these points.

The right hand rule was used to define the global reference system for all body segments, with the positive *x*-axis defined as the posterior to anterior axis, the positive *z*-axis defined as the inferior to superior longitudinal axis, and the positive *y*-axis as right to left. A minimum of three landmarks per segment were palpated on the lower extremities and digitized with the stylus while the subjects were standing with their arms relaxed by their sides. Bony landmarks on the pelvis, femur, tibia and fibula were palpated and digitized for transformation of sensor data to the local anatomic coordinate system.[112,113] To allow a clinically meaningful comparison as opposed to the use of a global reference system, local anatomic axes systems are advantageous to compare segments to one another. Points on the ASIS and PSIS determined the local coordinate system for the pelvis.[112] The greater trochanter and medial/lateral femoral epicondyles were used to set up the local coordinate system.[112] The local coordinate system for the shank was determined using the femoral epicondyles, medial and lateral malleoli, and medial/lateral joint lines.[112] Figure 3.2 displays sensor placement.

Figure 3.2. Location of sensors.

Data was captured at 100 Hz and low pass filtered at 30 Hz using a Butterworth 4th order zero phase shift filter (optimal filtering for smoothing of data without losing too many points, as noted with trials of different filter levels). Using a default set up with an analog anti-aliasing filter of 500 Hz, force plate data was sampled at 1000 Hz. The force plate was calibrated for each subject prior to testing. No other software filtering occurred, as this was sufficient. The shutter glasses were triggered to close during movement at a point when the force plate was unloaded at 5% of the subject's bodyweight or conversely when the weight of the subject was 95% of their maximum body weight as measured during calibration of the LabVIEW shutter glass program. The glasses shuttered down and remained off for a period of one second. In order to gain familiarity with the task and equipment worn during testing (sensors attached to body, headphones to hear tones, and shutter glasses with on/off mechanism carried in a fanny pack worn around their waist), subjects performed five practice trials. The testing protocol was initiated after the trial runs. Subjects were instructed to state whether they were having any discomfort or pain during or after testing. Figure 3.3 displays the laboratory set up.

Place at taped dot on Reebok Step Up down X axis (20 cm), hit OK

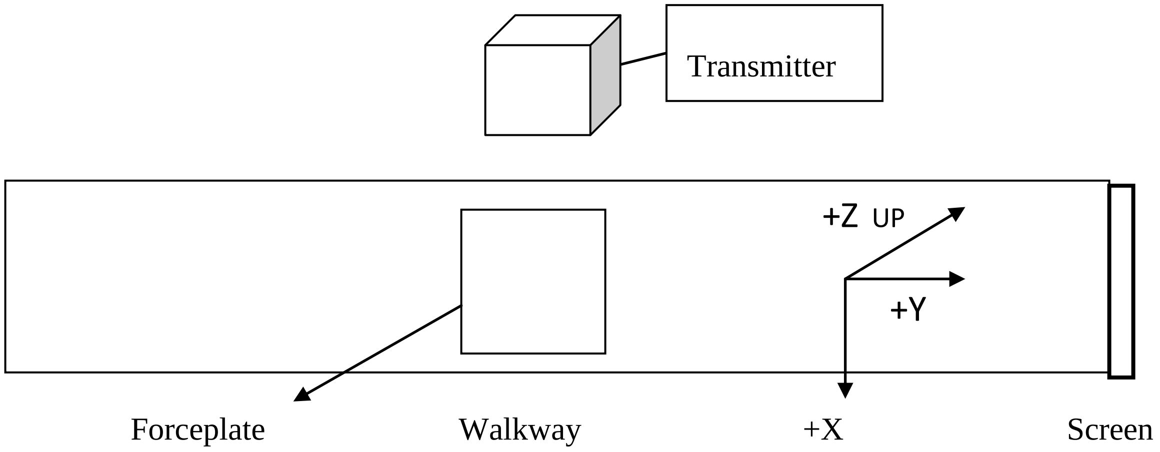

Figure 3.3. Laboratory set up.

The Motion Monitor system captured all kinematic and kinetic data and was exported for further analysis. Data was analyzed for the entire movement from sound of tone, which initiated the cut, to end of cut. To achieve this, each trial was viewed via video on the Motion Monitor system and data was cut at the end of the cutting motion so that extraneous movements after finishing the task were not included. Each trial was viewed and stopped three times and the average of those data points was chosen as the cut off point for data. To ensure consistency and improve accuracy of capturing the full movement without other unnecessary lower extremity motions, the chosen data points based on this visual inspection were within five data points each time. Subjects were instructed to stop at the end of the cut and hold the position until a researcher told them they could move back to the starting position.

Task

The task consisted of a cutting maneuver from a stationary athletic stance position. Subjects stood on a force platform with equal weight bearing across lower extremities. Both feet needed to be on the force platform to trigger the glasses based on the subject's bodyweight moving off of the force plate. If only one foot was on the force plate, the glasses would not shutter down properly if cutting to the same side as the foot on the force plate. It was also essential to keep the subject 'guessing' as to which side they would be cutting to. When ready, a ball was pitched from an automatic pitching machine directly to the subject from a distance of 15 feet. On the count "one and two and," a high or low pitch tone was heard in the headphones, indicating which direction the subject should cut. The high tone designated a right cut; the low tone designated a left cut. Visual conditions were randomized so that the glasses either disrupted vision for one second as the subject began the cutting movement, or remained open for the full of movement. Subjects were instructed to catch the ball and cut immediately to the direction designated by the tone. For a successful trial, subjects needed to catch the ball and hold their final position until given a verbal instruction to return to the starting position. A taped line angled at approximately 40 degrees to the right and left was secured on the testing platform to guide subjects. This angle is in accordance with values typically seen in a game situation.[115] Subjects were instructed to cut along the line of tape at a distance that was comfortable for them. Length of cut was collected and normalized to body height for analysis. Subjects completed 40 cutting trials in total, which were randomized for direction and vision, so that 10 trials for each condition were captured, i.e. cut left with vision, cut right with vision, cut left with vision disrupted, and cut right with vision disrupted. Motion analysis kinematic and kinetic data was collected for each trial. If subjects missed catching the ball or if data collected was not appropriate based on visual observation of Motion Monitor graphs, or if the glasses triggered too soon due to subject movement, extra trials were collected at the end of the original list of randomized trials to ensure 40 trials for analysis per subject.

Data Reduction

Raw kinematic data collected by the Motion Monitor system was then selected for further processing. Each trial was viewed and specific data was cut to capture only the task requirements. At this time, real-time graphs of data from the glasses, sound, and GRF were also viewed for appropriateness. This was a second check of proper timing of glasses shuttering and sound with movement (the first being at time of data collection by researcher running that computer station). During this evaluation of graphs, if there were trials that did not exhibit correct timing of the glasses shuttering down, those trials could not be included in the final data set. During these trials, the glasses either shuttered down too early or stayed down beyond the end of the task. These ‘incorrect’ data sets were present for both the ACL and healthy groups, while the ACL group displayed the majority of them. The total number of trials for all subjects was 1360. Seven healthy subjects and 8 ACL subjects had inaccurate trials due to the glasses shuttering down incorrectly. A total of 53 trials were eliminated from the final data set at this time, including 40 ACL trials and 13 healthy trials. The total number of trials that were eliminated was equal to 3.9% of the total number of trials, which was deemed acceptable.

Original variables included in the export file were 3D angles and moments for knee flexion, extension, abduction, adduction, external rotation and internal rotation for each leg and for each trial to the left and right with vision and without vision. Right and left leg data was changed to lead leg titles based on the direction of the cut, and additionally coded for ACL reconstructed limb/non-surgical limb or non-dominant/dominant healthy limb. For example, a trial for a subject with a left ACL reconstruction who performed a left cut would be coded ACL_lead, with data for the lead leg for all variables. Only the lead leg was analyzed upon landing from the right or left cut. Thus, the data was reduced to the last seconds based on impact of the lead leg to end of cut. Vision conditions were coded in a separate column.

Statistical Analysis

Pilot data was collected on three healthy female subjects and two ACL reconstructed females who performed the previously stated task. No comparative analysis was completed, but pilot data was used to authenticate the testing protocol and for power analysis. Taking the lowest estimation of effect size of all variables (.60), power analysis determined that the appropriate sample size to reach 80% power with one degree of freedom would be 12 per group. Based on these *a priori* findings, the target of a sample size of N=17 for the ACL group and N=17 for the healthy group, for a total of 34 subjects was set. This was to further attempt to achieve sufficient power given that no previous studies analyzed similar variables.

The primary dependent outcome variables analyzed included peak angles and moments for knee flexion/extension, abduction/adduction, and external/internal rotation. Independent variables included Group lead leg (ACL/non-dominant or Non-surgical/dominant) and vision (full/disrupted). Secondary variables included demographic variables of age, height, weight, cut length, and KT-1000 change. A 2 x 2 repeated-measures analysis of variance was used for all analysis. Post-hoc Tukey tests were calculated for all significant interactions to identify where these differences existed. The Tukey test sets a family-wise error rate that allows generous protection against a Type I error. For this project, a Bonferroni correction was not applied to the repeated measures analysis of variance (ANOVA), with the thought being that it was too strict. It was determined that post-hoc Tukey tests were sufficient to establish significant differences for this project's variables, given that they have not been previously studied. All test conditions for each dependent variable were tested for normality.

Comparisons

Group comparisons for demographic variables were analyzed using independent t-tests and are summarized in Table 3.1. A Pearson Product-Moment correlation was completed if significant differences existed and the demographic variable was a potential confounder. If a significant correlation existed with any dependent variable, an analysis of covariance (ANCOVA) was performed to determine if the demographic variable was significant and it impacted the overall analysis. The limitation with this analysis is that the ANCOVA does not allow for a repeated measures analysis, but rather uses a General Linear Models (GLM) analysis of variance. Body weight was the only potential confounder and was determined to be non-significant with the ANCOVA on the overall analysis.

Hypotheses 1 - 3. – A repeated measures, two-factor mixed model analysis of variance (ANOVA) was used to analyze the independent variables and their interactions. Independent variables included lead leg as the between-group factor (ACL reconstructed/Healthy Non-Dominant or ACL Non-Surgical/Healthy Dominant) and vision as the within group factor (full vision versus disrupted vision). As described previously, the dependent outcome variables were: peak abduction, adduction, flexion, extension, internal rotation and external rotation angles of the tibia relative to the femur at the time of landing; and corresponding peak abduction, adduction, flexion, extension, internal rotation and external rotation moments at the time of landing. Post-hoc Tukey tests were conducted for multiple comparisons of all pair-wise differences.

- Hypothesis 1: The ACL reconstructed (ACLR) individuals will present with differing 3D peak angles and corresponding moments at the time of t landing than healthy subjects.
- Hypothesis 2: When compared to non-disrupted vision, a disruption of vision will result in differing 3-D peak angles and corresponding moments at landing.

- Hypothesis 3: A combination of disrupted vision and ACLR will result in greater difference in 3-D peak angles and corresponding moments at landing.
    a. The combination of ACLR and disrupted vision will have a greater impact on kinematics and kinetics than ACLR with full vision.
    b. The combination of ACLR and disrupted vision will have a greater impact on kinematics and kinetics than healthy subjects with full vision or disrupted vision.

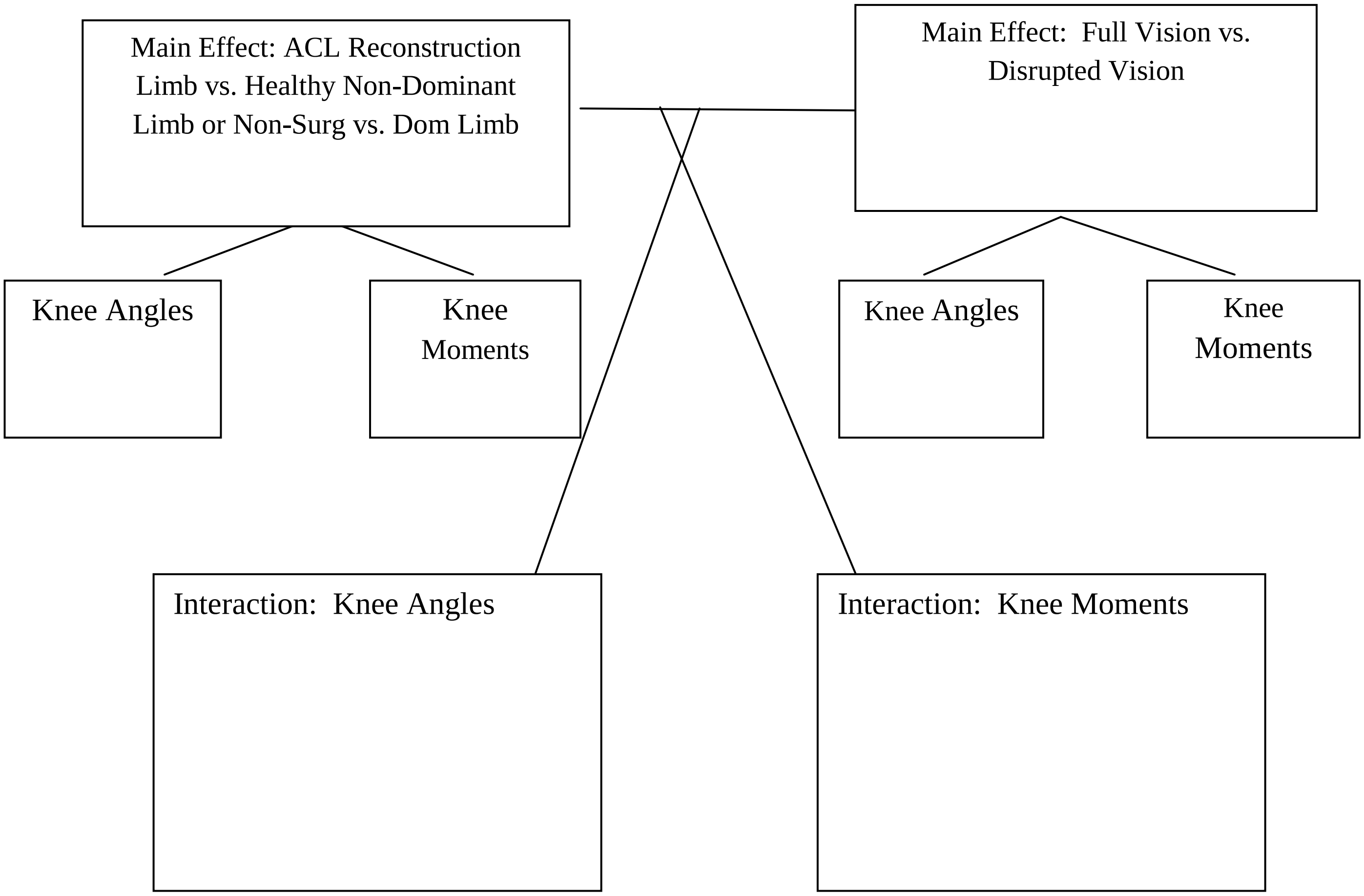

Figure 3.4. Data analysis schematic for repeated measures ANOVA's.

CHAPTER IV

RESULTS

Group Comparisons – ACL and Healthy

Knee Angles

Table 4.1 presents a summary of comparisons of mean peak angles and standard deviations for cutting tasks onto the ACL reconstructed group's non surgical leg and the Healthy group's dominant leg. A 2-way ANOVA and Tukey-Kramer Multiple-Comparison Test finds that during cutting, the ACL non-surgical leg demonstrates significantly less knee external rotation compared to the Healthy dominant leg (p=0.035). No other significant results are found between the ACL non-surgical leg and Healthy dominant leg for landing a cutting task in regards to mean peak knee angles.

Table 4.1: Mean peak knee angles demonstrating the main effect of ACL Non-Surgical knee compared to Healthy Dominant knee for cutting movements upon landing.

Mean Peak Angles (degrees)	**ACL Non-Surgical**	**Healthy Dominant**
Flexion	42.16±14.25	49.44±21.38
Adduction	40.35±21.38	47.60±16.34
External Rotation	24.73±15.80*	37.918±19.02*

* Statistically significant P<.05

Table 4.2 presents a summary of comparisons of mean peak angles and standard deviations for cutting tasks onto the ACL reconstructed group's surgical leg and the Healthy group's non-dominant leg. A trend towards significance is noted during cutting between groups for adduction, with the ACL surgical leg demonstrating greater adduction than the healthy non-dominant limb (p=0.0698). No other significant results are found between the ACL surgical leg and Healthy non-dominant leg for landing a cutting task in regards to mean peak knee angles.

Table 4.2: Mean peak knee angles demonstrating the main effect of ACL Surgical knee compared to Healthy Non- Dominant knee for cutting movements upon landing.

Mean Peak Angles (degrees)	**ACL Surgical**	**Healthy Non-Dominant**
Flexion	56.62±15.60	63.33±17.97
Adduction	23.27±16.15**	13.39±14.08**
External Rotation	12.93±13.97	10.0413±8.40

* Statistically significant P<.05
** Trend towards significance P<.07

Knee Moments

Table 4.3 presents a summary of comparisons of mean peak moments and standard deviations for cutting tasks between the ACL non-surgical leg and Healthy dominant leg. The ACL non surgical leg displays a significantly larger knee abduction (p=0.024) and internal rotation (p=0.012) moments compared to the Healthy dominant leg during a cutting task. In addition, a trend is also noted for the ACL non-surgical leg, with more extension (p=0.062) knee moment compared to the Healthy dominant leg. No other significant results are found between the ACL non-surgical leg and Healthy dominant leg for cutting tasks in regards to mean peak knee moments.

Table 4.3: Mean peak knee moments demonstrating the main effect of ACL Non-Surgical knee compared to Healthy Dominant knee for cutting movements upon landing.

Mean Peak Moments (Nm/kg/m)	**ACL Non-Surgical**	**Healthy Dominant**
Extension	0.0505±9.34E-02**	0.0101±7.51E-03**
Abduction	0.0329±3.22E-02*	0.0151±7.06E-03*
Internal Rotation	0.0207±2.25E-02*	0.0062±5.70E-03*

* Statistically significant P<.05
** Trend towards significance P<.07

Table 4.4 presents a summary of comparisons of mean peak moments and standard deviations for cutting tasks between the ACL surgical leg and Healthy non-dominant leg. The ACL surgical leg shows significantly less extension (p=0.049) knee moment compared to the Healthy non-dominant leg. Also a trend is noted for less internal rotation (p=0.058) on the ACL surgical leg in contrast to the Healthy non-dominant leg. No other significant results are found between the ACL surgical leg and Healthy non-dominant leg for cutting tasks in regards to mean peak knee moments.

Table 4.4: Mean peak knee moments demonstrating the main effect of ACL Surgical knee compared to Healthy Non- Dominant knee for cutting movements upon landing.

Mean Peak Moments (Nm/kg/m)	**ACL Surgical**	**Healthy Non-Dominant**
Extension	0.0305±3.38E-02*	0.0135±5.82E-03*
Abduction	0.0340±4.52E-02	0.0158±1.17E-02
Internal Rotation	0.0199±1.89E-02**	0.0100±9.43E-03**

* Statistically significant P<.05
** Trend towards significance P<.07

Group Comparisons – Vision Intact and Disrupted

No significant main effects of vision are found. Table 4.5 and 4.6 outline the results of mean peak angles, mean peak moments, and standard deviations for cutting tasks for combined groups of Healthy non-dominant and ACL surgical legs with vision intact and disrupted, as well as combined groups of Healthy dominant and ACL non-surgical legs with vision intact and disrupted.

Table 4.5: Mean peak knee angles and moments demonstrating the main effect of vision on Healthy Non-Dominant/ACL Surgical knee for cutting movements upon landing.

Mean Peak Angles (degrees)	**Vision Intact for Non-Dominant/ACL Surgical**	**Vision Disrupted for Non-Dominant/ACL Surgical**
Flexion	60.24±17.49	59.72±16.83
Adduction	18.60±16.05	18.06±15.86
External Rotation	11.65±11.43	11.31±11.80
Mean Peak Moments (Nm/kg/m)		
Extension	0.0224±2.75E-02	0.0217±2.39E-02
Abduction	0.0262±3.90E-02	0.0235±2.87E-02
Internal Rotation	0.0151±1.60E-02	0.0148±1.55E-02

* Statistically significant P<.05

Table 4.6: Mean peak knee angles and moments demonstrating the main effect of vision on Healthy Dominant/ACL Non-Surgical knee for cutting movements upon landing.

Mean Peak Angles (degrees)	**Vision Intact for Dominant/ACL Non-Surgical**	**Vision Disrupted for Dominant/ACL Non-Surgical**
Flexion	45.08±17.99	46.52±19.04
Adduction	43.77±19.59	44.18±19.17
External Rotation	31.16±18.40	31.49±19.04
Mean Peak Moments (Nm/kg/m)		
Extension	0.0267±4.03E-02	0.0339±8.92E-02
Abduction	0.0234±1.99E-02	0.0246±2.92E-02
Internal Rotation	0.0136±1.83E-02	0.0133±1.77E-02

Vision Comparisons by Group – Intact Vision and Disrupted Vision

Knee Angles

Interaction effects were found between the ACL non-surgical knee versus Healthy dominant knee, as seen in Table 4.7. The ACL non-surgical knee with vision exhibits significantly decreased knee external rotation angles compared to Healthy dominant knee with both intact and disrupted vision. The ACL non-surgical knee with vision disrupted also presents significantly less knee external rotation angles compared to Healthy dominant knee with intact and disrupted vision. A trend towards significance was found for the ACL non-surgical knee without vision, which displays decreased knee flexion angles compared to the Healthy dominant knee without vision at landing . Another trend was found between the ACL non-surgical knee with vision demonstrating decreased knee flexion angles compared to Healthy dominant knee without vision upon landing. No additional significant results are found during cutting tasks while assessing the interaction effects of vision between ACL non-surgical and Healthy dominant knees. No interaction effects are found for vision and the ACL surgical leg or Healthy non-dominant leg, which is summarized in Table 4.8.

Table 4.7: Mean peak knee angles demonstrating significant interactions of ACL Non-Surgical knee compared to Healthy Dominant knee for cutting movements upon landing

Mean Peak Angles (degrees)	**ACL Non-Surgical**		**Healthy Dominant**	
	Intact Vision	**Disrupted Vision**	**Intact Vision**	**Disrupted Vision**
Flexion	43.49±14.16**	40.82±14.64 **	46.67±21.49	52.21±21.55**
Adduction	40.24±21.77	40.46±21.66	47.30±17.05	47.90±16.11
External Rotation	25.75±17.08*	23.71±14.87 *	36.57±18.56 *	39.26±19.96*

* Statistically significant P<.05

** Trend toward significance P<.07

Table 4.8: Mean peak knee angles demonstrating significant interactions of ACL Surgical knee compared to Healthy Non- Dominant knee for cutting movements upon landing

Mean Peak Angles (degrees)	**ACL Surgical**		**Healthy Non-Dominant**	
	Intact Vision	**Disrupted Vision**	**Intact Vision**	**Disrupted Vision**
Flexion	57.01±16.32	56.24±15.35	63.47±18.51	63.19±17.97
Adduction	23.71±16.43	22.84±16.36	13.50±14.35	13.28±14.23
External Rotation	13.23±13.95	12.63±14.41	10.08±8.35	10.00±8.71

* Statistically significant P<.05

** Trend toward significance P<.07

Knee Moments

The impact of vision is not statistically significant during any of the cutting tasks for ACL non-surgical, Healthy dominant, ACL surgical, or Healthy non-dominant legs regarding knee moments as seen in both Tables 4.9 and 4.10.

Table 4.9: Mean peak knee moments demonstrating significant interactions of ACL Non- Surgical knee compared to Healthy Dominant knee for cutting movements upon landing

Mean Peak Moments (Nm/kg/m)	**ACL Non-Surgical**		**Healthy Dominant**	
	Intact Vision	**Disrupted Vision**	**Intact Vision**	**Disrupted Vision**
Extension	0.0419±5.29E-02	0.0591±0.1226	0.0114±8.29E-03	0.0088±6.65E-03
Abduction	0.0300±2.56E-02	0.0359±3.82E-02	0.0168±8.40E-03	0.0133±5.11E-03
Internal Rotation	0.0199±2.37E-02	0.0214±2.20E-02	0.0074±6.79E-03	0.0051±4.27E-03

* Statistically significant P<.05

** Trend toward significance P<.07

Table 4.10: Mean peak knee moments demonstrating significant interactions of ACL Non- Surgical knee compared to Healthy Dominant knee for cutting movements upon landing

Mean Peak Moments (Nm/kg/m)	**ACL Surgical**		**Healthy Non-Dominant**	
	Intact Vision	**Disrupted Vision**	**Intact Vision**	**Disrupted Vision**
Extension	0.0314±3.67E-02	0.0297±3.18E-02	0.0134±6.27E-03	0.0136±5.54E-03
Abduction	0.0366±5.24E-02	0.0313±3.80E-02	0.0158±1.28E-02	0.0157±1.09E-02
Internal Rotation	0.0200±1.91E-02	0.0199±1.92E-02	0.010±1.048E-02	0.0098±8.57E-03

* Statistically significant P<.05

** Trend toward significance P<.07

CHAPTER V

DISCUSSION

This research was conducted to investigate differences in specific 3-D knee kinematics and kinetics during the landing portion of a cutting task for female subjects with an ACL reconstruction compared to healthy subjects. Additionally, this research explored the impact of visual disruption on 3-D knee kinematics and kinetics during the same task. Because previous ACL research with visual disruption during cutting tasks is minimal, there is a lack of evidence to support our study's vision results. Where earlier research used blindfolds to completely block vision throughout a lower extremity task, the current study allowed for a realistic simulation of visual disruption with the use of shutter glasses to turn vision off and then on again during the progression of an athletic maneuver.

Group Comparisons – ACL and Healthy

Our results provided evidence that following ACL reconstruction, subjects demonstrate significantly increased knee extensor moments on their ACL reconstructed leg during cutting tasks. This tendency to land in a more extended position has been associated with higher ACL strain.[24] It has been postulated that an inability to decrease knee extensor moments during a landing task increases knee compression and anterior shear force of the tibia on femur. This appears to be characteristic of non-contact injury mechanisms to the ACL.[61] A greater extensor moment during landing may be due to poor timing of quadriceps and hamstring co-activation. Vairo et al suggested that greater preparatory and reactive co-contraction of the quadriceps and hamstrings related to decreased anterior tibial shear force and loading on the ACL.[62] A general lack of hamstring activation or poor preparatory or reactive contraction of the hamstrings concomitantly with the quadriceps appears to increase knee extension when landing, secondary to over activation of knee extensor muscles compared to knee flexors.[62] In the current study, greater extensor moments may be related to this pattern of greater quadriceps activation. This pattern appears to pull the tibia anteriorly, placing the ACL on stretch and therefore in a vulnerable position. Alternatively, when healthy subjects land with increased knee flexion, there may be greater protective hamstring and quadriceps co-activation. This provides dynamic joint stabilization, as the hamstrings reciprocally pull the tibia posteriorly, decreasing the stress placed on the ACL. A pattern of decreased hamstring activation upon landing in ACL deficient females may be due to damaged skin, muscle, tendon or ligament receptors; all of which may decrease postural stability at the knee.[39]

The current results showed a trend of increased knee extensor moments when landing on the non-surgical knee for ACL reconstructed subjects, as compared to healthy subjects’ non-dominant knee. No difference was found in knee flexion angles between these two groups in landing, but it appears that the ACL reconstructed subjects still created a greater moment to resist knee flexion. A greater extensor moment suggests that the knee has to create a greater force to resist knee flexion. Resultantly the knees anatomical structures, including its ligaments, must be able to withstand this greater force to avoid injury or complete rupture. Furthermore, previous research has shown that increased loads, such as extensor, rotational, and abduction moments at the knee are predictive of ACL injury.[57, 59]

ACL reconstructed subjects showed a trend toward an increased internal rotation moment on their reconstructed knee when compared to healthy subjects' non-dominant knees. They also demonstrated a significant increase in internal rotation moment on the non-surgical knee when compared to healthy subjects' dominant knees. The ACL non-surgical knees also had a concurrent trend of less external rotation angles than healthy dominant knees. These internal rotation moments increase the force at the knee and on its ligaments, especially when they are compounded with increased extension and abduction moment mechanisms that ACL reconstructed individuals in this study appear to use for compensation. This suggests that the ACL reconstructed individual may alter the way she lands, putting either knee at risk for a new ACL rupture due to the greater forces acting on the knee.[59] On the other hand, adopting a landing pattern with decreased external rotation, as the ACL non-surgical subjects did, may be explained as this group being apprehensive secondary to their previous injury and trying to control knee movements that feel risky. This pattern likely feels safer and more controlled as tibial rotation has been identified as a mechanism of ACL injury.[8]

Previous research has shown that healthy females tend to land with significantly increased knee abduction during cutting tasks, which may increase the risk of non-contact

ACL injuries.[64,52,60] A trend was noted in this data with the ACL surgical knee landing with greater adduction compared to the non-dominant healthy knee. The adduction angles revealed in our study do not support previous research indicating that women in general have increased dynamic tibio-femoral abduction angles. However, research has also demonstrated decreased abduction angles in healthy females post neuromuscular re-training with balance and plyometric exercises.[50, 52-54, 56] The intent of these neuromuscular training programs was to decrease ACL injury risk by decreasing dynamic valgus. [50, 52-54, 56] The ACL reconstructed subjects in our study may have undergone physical therapy or other retraining programs post ACL reconstruction, which would have focused on re-training the knee to land with decreased valgus in order to decrease risk of re-injury, thus explaining why our data showed ACL surgical knees landing with greater adduction angles compared to their non-dominant healthy knees. Despite this, our data did reveal that ACL reconstructed subjects demonstrate a significantly greater abduction moment when cutting and landing on their non-surgical leg.

This disagreement with the literature may be due to the methods in which the data was taken. For example, previous research has mostly taken data from the cutting or push-off leg in a cutting task, whereas our data was taken from the landing leg in a cutting task. This data may better equate to a landing from a jump, however most jump-landing studies have looked at vertical landings. Rather, our study had a lateral component to the landing, based on the cutting movement pattern. There may be a difference in kinematics between these two different movements. Regardless, this data did show that ACL reconstructed individuals landed with a different pattern on both their surgical and non-surgical legs than healthy controls. This may suggest that those who sustain ACL injury may inherently have movement patterns that put them at less risk for re-injury to their ACL reconstructed limb (decreased abduction angle) and more risk for their non-surgical side risk (greater internal rotation and extension moments).

Vision Comparisons – Vision and Disrupted Vision

Vision is a vital sense that individuals rely on to complete many complex tasks. In landing and cutting tasks, it is thought that people use a combination of vestibular, visual, and proprioceptive input to correctly adapt to the environment.[69] Given that this is the first study where vision has been randomly disrupted and turned back on during movement, there is no research to directly compare our findings. Previous studies are inconclusive as to the extent of vision's role in protection from injuries during a cutting task. In individuals without ACL injury, it is thought by some authors that the activation patterns prior to landing a cutting task are very similar regardless of vision or no vision. Liebermann and Goodman speculated that these findings were due to the subjects' ability to use other processes such as a temporal estimation of the landing to compensate for continuous visual input.[68] On the contrary, other studies suggest that the predictability of the landing is important when vision is disrupted.[69] Thompson and McKinley found that the activation of lower extremity musculature is actually delayed during a landing task in which vision is randomly disrupted.[69]

When looking at the results from the current study, it must be noted that vision as a main effect was not significant in any case. When collapsing both groups and only looking at vision conditions, there were no significant differences noted. However, when taking both knee and vision into account, our data suggests that while cutting onto the non-surgical knee with visual disruption, ACL reconstructed females demonstrated decreased tibio-femoral external rotation and knee flexion compared to healthy subjects who landed on their dominant knee. This finding may be explained by ACL subjects being more apprehensive due to a previous injury, therefore they may use a movement pattern that feels safer and more controlled, limiting tibial rotation. On the other hand, lack of knee flexion when landing can again be a result of weak quadriceps and other lower extremity musculature, or poor timing of hamstrings to effectively co-contract with quadriceps. Landing on a stiffer knee suggests that the subject may not be able to decrease ground reaction forces or anterior tibial shear forces, putting the ACL and other knee structures at risk for injury.[24] Therefore, when performing complicated tasks, vision may more greatly impact subjects at risk for ACL rupture.

Limitations

It is important to be aware of the limitations of our research. The simplicity of the cutting task as well as the unrealistic setting in which the task was performed may be considered a limitation. The power of the study may have been reduced due to the small sample size that was obtained for this study. In addition, simple human error with set up and data reduction may have impacted the results. While using the Flock of Birds system, detection angles may have decreased precision with placement of electromagnetic sensors on the skin rather than in bone using bone pins. Additionally, there may have been human error involved in the timing of the pitching machine and the tone signaling the cutting direction. Given the subject population for the current study, we are not able to generalize our results to men of any age or women under the age of 18 or over 45. We are also not able to compare acute versus chronic ACL reconstructions as most of our subjects were ±4.6 years post surgical reconstruction. Further research could focus on developing a study in which the subject is able to perform a game-like cutting maneuver in which he or she is not restricted by the environment or equipment. In addition, it would be useful to conduct a study with similar visual disruptions in which the subjects were required to complete a more complex, game-like task.

CHAPTER VI

CONCLUSION

Our research concluded that even years after ACL reconstruction, subjects demonstrated abnormal movement patterns when compared to healthy subjects. These changes in movement patterns may be due to strength imbalances, altered biomechanics, and neuromuscular dysfunction after ACL reconstruction.[9] The ACL reconstructed subjects in the current study effectively landed in patterns that would likely promote greater forces at the knee and on its supporting tissues. Furthermore, knee angle differences were observed in landing that might be a compensatory mechanism to prevent further injury or because of strength and control deficits. Physical therapy rehabilitation efforts should address changes in strength, neuromuscular control, and compensation patterns following ACL reconstruction in order to minimize abnormal movement patterns and allow for a more complete recovery. Though further research in the area of visual disruption and ACL injury needs to be conducted, our research suggests that visual disruptions may impact knee kinematics by reducing angular movement at the knee in landing, thus minimizing the variability of knee movement. This may reduce the risk for injury by avoiding vulnerable movement patterns, however resulting in a decreased ability to accommodate to potentially greater forces at the knee. With this new evidence, further research is needed to determine if an ACL rehabilitation program should include visual disruption training to reduce risk of ACL injury. In summary, ACL reconstructed individuals continue to demonstrate abnormal movement patterns persisting years later, which may lead to continued risk for re-injury. Rehabilitation efforts should focus on normalizing these movement patterns to prevent possible further injuries.

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