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Influence of Fatigue and Anticipation on Knee Kinematics and Kinetics during a Jump-cut Maneuver

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ABSTRACT

BACKGROUND AND PURPOSE: Injuries to the anterior cruciate ligament (ACL) are common among athletes, particularly females. This research aims to reconcile the anticipated and unanticipated movement pattern of jumping and cutting with fatigue for both genders. The research will compare lower extremity biomechanics of a jump-cut after a sports specific fatigue protocol, intending to examine movement patterns which may predispose the subject to ACL injury.

METHODS: Twenty healthy subjects were studied (24.9±3.3yrs), including 10 females. A 3D electromagnetic system measured knee kinematics and kinetics during jump-cut tasks. The jump-cut task included anticipated (A) and unanticipated (UA) trials to both directions. For the UA trials, the subject was unaware of the cutting direction until initiation of the task. The fatigue protocol consisted of jumping, sprinting, step-ups, and agility. Subjects completed the jump-cut task again in a fatigued state. A repeated measures ANOVA was used to analyze peak and mean angles, moments and ground reaction forces (GRF), with post-hoc Tukey tests for significant findings between factors (gender, pre/post-fatigue, A/UA).

RESULTS: Significant main effects were found for gender and IR/ER and ADD/ABD peak and/or mean angles, and ADD/ABD moments; pre and post-fatigue and IR/ER, EXT/FLEX, and ADD/ABD peak and/or mean angles, and ADD/ABD moments; A/UA conditions and IR/ER and ADD/ABD peak and/or mean angles. Significant interactions existed for gender and A/UA for EXT moment and for pre/post-fatigue and A/UA for EXT moment, IR moment and IR/ER angles.

CONCLUSION: Subjects demonstrated significant changes in knee kinematics and kinetics. Fatigue and A/UA states influenced knee movement patterns in variable ways, which may indicate an attempt to safely land and cut. Additionally, females demonstrated biomechanics that may increase their risk for ACL injury relative to males. Gender, fatigue, and A/UA conditions had an impact on one another and should be considered when designing sports training programs to reduce risky movement patterns.

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

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CHAPTER I

INTRODUCTION

Background

The anterior cruciate ligament (ACL) is a ligament within the knee joint that attaches from the anterior-medial tibia to the posterior-lateral femoral condyle. The ACL prevents anterior tibial translation in open-chain movements and therefore posterior femoral translation in a closed-chain mechanism. Another function of the ACL is to prevent excessive tibial rotation in closed-chain mechanisms. Overall, the ACL provides approximately 90% of the stability in the knee[1]. ACL injury prevalence is a rising problem with sources citing estimated injuries per year at 80,000 up to 250,000 [1-3]. ACL injury is most prevalent in patients 15-45 years old likely associated with more active lifestyles and involvement with sports[1]. These injuries may result from both contact and non-contact mechanisms. Non-contact mechanisms contribute to approximately 70% of ACL injuries[1,4]. Treatment following ACL injuries may involve either conservative rehabilitation or surgical reconstruction. Approximately 50,000 to 100,000 ACL reconstructions are performed each year in the U.S. The cost of a single reconstructive ACL surgery has been estimated to be $17,000[5]. When comparing the cost of reconstruction versus conservative rehabilitation, operative repair has been shown to be more cost effective with research citing a “mean lifetime cost” of $38,121 for ACL reconstruction patients versus $88,538 for rehabilitation patients[6]. Regardless of post-ACL injury treatment there is an increased risk of osteoarthritis (OA) in the future, which has implications for future overall costs and management of symptoms. Re-injury rates of reconstructed ACL’s are fairly low at 2.6% re-rupture rate over a mean of 2.5 years after surgery[1]. However, post ACLr studies have found that young athletes ranging from 15-18 years old have an increased injury rate of 22% on the contralateral leg[7].

Research has widely shown that there is a significant disparity between ACL prevalence in females versus males. According to the National College Athletic Association (NCAA) women playing sports are 2 to 8 times more likely to sustain an ACL injury their male peers[1]. Numerous studies have been conducted in an effort to examine what may be leading to the significant disparity between men and women. Research has supported the notion that the cause of disparity may be multifactorial including, anatomic/structural factors, hormonal factors, and neuromuscular and biomechanical factors. In regard to anatomic/structural factors, research has proposed that a difference between genders, including increased Q angle, pelvic width, and structural laxity of stabilizing elements in the knee noted in females, are possible sources of the disparity[6]. Hormonal factors, including hormonal fluctuations during the menstrual cycle may be implicated in the increased rate of ACL tears in females as the ACL itself has receptors for estrogen[6]. According to research, estrogen levels may play a role in ACL tears due to the negative effects of estrogen on collagen and connective tissue strength[6]. Many studies have found females use different neuromuscular patterns during athletic maneuvers than males, which could put them at increased risk for load placed on the ACL[8-15]. One well studied reason may be attributed to asymmetrical lower extremity muscular activation of the quadriceps and the hamstrings during these maneuvers. Many researchers have found that females tend to activate their quadriceps more than their hamstrings, causing an increased anterior shear force of the tibia on the femur without counter activation to slow down the shearing force[8,10-11,12-13]. This difference in neuromuscular activation pattern could be due to the variation of kinematics between genders, which may be contributing to an increased risk to the ligamentous structure[8-13].

Biomechanically, numerous research studies have found that women tend to land in a more valgus position when compared to their male partners, which is a position of increased risk for the ACL[16]. Research has also supported the fact that women tend to land from jumps with a more extended knee[2,17-18]. However, a more widespread review of the literature indicates that there are relative inconsistencies in results as well as numerous theories that have arisen in regard to gender differences in lower extremity biomechanics and findings may be influenced by things such as training, experience level, and the specific task[19-20].

ACL Reconstruction

Several researchers have shown impaired knee joint biomechanics post ACL reconstruction, regardless the type of reconstruction. It has been found that after a reconstruction, excessive tibial rotation is still occurring in high demanding activities involving anterior and rotational loading of the knee. Additionally results suggest impaired neuromuscular control of the knee regardless of regained muscular strength. The impaired biomechanics of the knee may cause a change in landing patterns leading to loading cartilage instead. As a result of the change in mechanics there is an increased risk of developing knee osteoarthritis overtime. Furthermore if a muscle imbalance is present, the risk of re-injury is increased. After reconstruction, commonly quadriceps and hamstring strength deficiencies are present. This can be due to loss of afferent reaction from the ACL to gamma motor neurons. Neuromuscular control in reference to electromechanical delay can be a factor when looking at reconstructed ACL knees as well. If there is a delay between the onset of muscle stimulation and the force produced by the contraction, it can put the knee at risk of injury. This is especially concerning for the hamstrings as they are the antagonist to quadriceps, and preventing some of the anterior shearing forces mentioned above. Players returning to sport need to prepare to participate in high intensity activities. Fatigue is a concern, and needs to be simulated at the level the player wants to return to in order to show any deficits that may be present. Overall, it is important to acknowledge that biomechanics and neuromuscular control are affected after an ACL reconstruction, and these need to be addressed before allowing a player to return to higher intensity activities or sport[21].

Influence of Fatigue

Many studies have examined the effects of fatigue of healthy individuals and how these effects may influence a change in the kinetics and kinematics of the lower extremity. Healthy athletes who are exercising in a fatigued state demonstrate changes in the knee kinetics and kinematics, which include landing in a more extended position[22-25], increased knee abduction moment[26], and a significant increase in knee valgus moment[27-28]. These two changes, along with other components, indicate an increased strain on the ACL and therefore an increased risk for ACL injury.

When looking at the effect of fatigue in individuals with ACLR, the overarching theme throughout multiple studies found that individuals with an ACLR were weaker on their involved leg at baseline than their uninvolved side or than the control group. However, post fatigue there was no difference, suggesting that there was atrophy of the fast twitch (type II) fibers while the endurance (type I) seemed to not be affected from the ACLR surgery and rehabilitation. Because of this finding, many studies suggested including high burst, power exercise to help reduce the loss of the type II fibers[21,29-37]. As for healthy individuals, conclusions from previous research determine the most effective protocol will include the subject being in a fatigued state, will include unanticipated trials to include central and peripheral fatigue effects[22-23,25,38], and will include various tasks, such as sidestep[25,38-39] and different drop heights[27], to fully produce the effects of fatigue. Therefore stressing ACLR patients in tasks that fatigue a healthy individual will be imperative to demonstrate any remaining deficits causing vulnerability of the ACL and knee.

Purpose

The purpose of this study is to determine the differences in movement patterns of the lower extremity between healthy females and males, during pre and post fatigue testing, anticipated and unanticipated trials, as well as interactions between these factors. This research may identify whether a dysfunctional or high risk movement pattern may predispose an individual to possible injury.

Hypotheses

Based on previous research, we hypothesized that post-fatigue jump-cut trials and unanticipated jump-cut trials would result in riskier knee kinematics and kinetics associated with ACL injury, regardless of gender. However, we hypothesize that females would demonstrate greater changes in knee kinematics and kinetics in comparison to their male counterparts during all jump-cut trials.

Chapter II

REVIEW OF LITERATURE

Anterior Cruciate Ligament (ACL) injuries are one of the most common knee injuries in sports with a higher incidence occurring in women. Many studies have been performed to determine risk factors, and gender differences that increase one's susceptibility to this serious ligamentous injury. Determining risk factors has led to development of potential prevention programs. A number of possibilities for the difference in genders have been studied. Some of these possibilities are differences in: anatomical structures, biomechanics, neuromuscular, and hormonal factors.

Biomechanics

Upon reviewing the literature, there are numerous studies that examine the gender differences in lower extremity biomechanics. Research protocols have involved various populations, tasks performed during course of observation, and purpose of observation (i.e. assessment of kinematics, kinetics, joint angles, moments, etc.). For the purpose of reviewing the literature for the currently proposed study, articles including a male and female population in the approximate age range of 18-35 years old were included in order to be most applicable to the anticipated target population.

As previously mentioned, much research has been done in regard to the biomechanical differences in landing between genders. However, some studies have chosen to examine drop landings while others have chosen other forms of jumping and landing. For the purposes of this literature review, studies examining drop landings will be synthesized first. Russell et al.[16] examined differences in knee valgus position and gluteus medius contraction upon landing from a unilateral drop-landing between genders. The study included 32 (16 female, 16 male) participants between the ages of 18 and 30 years old, deemed healthy and free from lower extremity injury. Subjects were instructed to complete a drop-landing onto a force plate from a box height of 60cm, landing on their dominant leg only. Analysis was performed at points of both initial contact and maximum knee flexion. Results indicated that females tended to land in a more valgus position while men landed in a more varus position, which is in agreement with the findings of Sigward et al.[4] and McLean et al.[2] Russell et al.[16] hypothesized that this finding may give evidence to the notion that females are "pre-programmed" with different landing patterns, as this noted gender difference occurred at initial contact. Further analysis through the motion until maximum knee flexion was reached demonstrated that females maintained a greater relative knee valgus position throughout the motion as well. This finding may give support to the hypothesis that women are unable to correct for their initial landing errors throughout the remainder of the landing. Based on the valgus alignment with which female subjects landed, researchers reported that this finding supports the ligament dominance theory in which females absorb landing forces via ligamentous/passive structures versus musculature. The reason for this is because the musculature acting on the knee is primarily oriented to absorb landing forces in the sagittal plane, whereas the valgus motion is a frontal plane motion and therefore requires increased shock absorption from the ligamentous structures which are oriented in that anatomical plane. In regard to gluteus medius activity, there were no significant differences between genders and therefore it is not thought to be the core cause of the differences in knee position upon landing.

Orishimo et al.[19] also chose to examine gender differences in unilateral drop-landing mechanics using the particular population of professional dancers. Thirty-three (12 males, 21 females) healthy subjects from professional dance companies in New York participated in the study which involved performing single-limb landings onto a force plate from a height of 30cm. In accordance with the aforementioned study performed by Russell et al.[16], this study also analyzed the movement from initial contact to maximum knee flexion. However, in contrast to the results found by Russell et al.[16], there were no significant differences found between genders in regard to frontal and sagittal plane angles of the lower extremity. Similarly, the study found no significant differences in landing patterns between genders in all other variables measured including: ground reaction forces, loading rate, joint moments, and peak total support moment. The authors noted that both genders demonstrated proper landing techniques that did not fit patterns commonly associated with risky movements. The reason cited for these findings is primarily believed to be due to the experience level and background of extensive training regarding safely landing from jumps that is associated with being a professional dancer. Therefore, this study gives evidence to the concept that the increased prevalence of ACL injury seen in the female population could be due to inexperience or inadequate training.

In a similar study by Huston et al.[17], researchers also examined knee angles in both genders at initial contact following a drop-landing from heights of 20cm, 40cm, and 60cm. Included in the study were 20 (10 female, 10 male) healthy, physically active, subjects with a mean age of 28 years. When performing drop-landings, subjects were cued to land on or near a target 40cm from the jumping platform. Results varied across jump heights but the trend remained the same; for both the 60cm and 40cm height, female participants landed in a more extended position in comparison to their male counterparts. According to the researchers, “Every degree that the knee is straighter will increase the ground impact force by approximately 1%.” Therefore, this study provides one plausible explanation for the increased ACL injury rate seen in the female population. For the test height of 20cm, no significant differences were found between genders in regard to knee angle at initial contact. There were also no significant differences between genders for the 20 cm height in regard to the ‘range of knee flexion’ and ‘maximum knee flexion angles’.

Schmitz et al.[18] conducted a related study also examining gender differences in hip, knee and ankle angles when performing a single-limb drop landing, while also studying joint energetics and GRF. Twenty-eight (14 males, 14 females) college students deemed recreationally active and in good health participated in the analysis which included the performance of unilateral drop-landings from height of 30cm with the aim of landing on the force plate located 10cm forward. In comparison to the results of Huston et al.[17] both studies indicated that females tended to display a more extended landing pattern. However, in contrast to the findings of Huston et al.[17], Schmitz et al.[18] found that joint angles at initial contact were not significantly different but rather the total amount of joint range was significantly different between genders with females generating less hip and knee flexion. Females were also found to land with higher GRF in comparison to their male counterparts. Both genders demonstrated a trend towards absorbing most of the energy at the ankle, however females absorbed energy at this joint to a higher extent. In combination, these findings indicate that the female population may perform drop-landings with a ‘stiff’ landing pattern which leads to decreased energy dissipation by the lower extremity extensor musculature and therefore places more relative stress on the ligamentous structures, including the ACL, and yields support for the “ligament-dominant” theory, in agreement with Russell and colleagues[16].

In yet another study examining gender differences from drop-landings, Decker et al.[40] sought to analyze gender differences in regard to joint angles, moments and energy absorption patterns. Twenty-one (12 male, 9 female) healthy individuals classified as active based on their participation in competitive intramural sports participated in the study performing bilateral drop-landings from a 60cm height with only one foot contacting the force plate upon landing. Results, in contrast to Schmitz et al.[18], indicated that there were no significant differences between genders in maximum knee flexion during the drop-landing. However, in accordance with Huston et al.[17], females landed in a more extended position at initial contact. Again, this position places the hamstrings at a disadvantage to protect against anterior tibial shift. In contrast to Schmitz et al.[18], both genders used the knee as the key site for energy dissipation in comparison to the ankle, with females absorbing most energy from the knee and ankle and males demonstrating a more global energy absorption including the hip. Based on key findings, Decker and colleagues[40] define the landing pattern of both genders in their study as "soft", although there were still significant differences in the landing style. Researchers hypothesized that because females landed in a more extended position but yet reached a similar maximum knee flexion as their male counterparts, females may move through a greater range of motion during the landing process in order to absorb the forces of landing. GRF were not significantly different between genders, which according to researchers, may be due to what they called a "pre-planned muscular landing strategy" employed by females in this study via the ankle plantar-flexors counterbalancing the more extended position with which the female population landed.

Aside from drop-landings, many other studies have analyzed gender differences when performing jump landings. Lam and Valovich McLeod[41] studied gender differences in the landing styles of 215 (116 male, 99 female) collegiate athletes, in current good health, when performing a jump landing task. Analysis was performed via use of the Landing Error Scoring System (LESS). In regard to the jump landing task, subjects were instructed to jump from a height of 30 cm, towards a selected target at a distance of 50% the height of the subject, and perform a counter jump to maximum vertical height upon landing from the original jump. Results found different trends in landing patterns between genders. Landing patterns of the male participants included characteristics such as a more prominent heel strike landing at initial contact, a more extended position at initial contact, and a more erect trunk position. In comparison, females demonstrated greater knee valgus throughout the landing movement. Therefore, this study found that both males and females in this population demonstrated some form of at-risk landing pattern. The difference between genders arose in regard to the plane of movement of the errors, with males performing more unsafe behaviors in the sagittal plane, and female at-risk behaviors occurring more in the frontal plane.

Lyle et al.[42] used a similar methodology as aforementioned in Lam and Valovich McLeod[41], with the additional inclusion of a test for lower extremity dexterity as one of the primary purposes of the study was to determine if dexterity was a contributing factor to gender differences in ACL injury. Subjects included 29 (14 female, 15 male) healthy, soccer players with an age range of 15-18 years old and no prior history of ACL injury or knee operation. Methodology included both a test for lower extremity dexterity and a jump task in which participants were required to jump from a height of 30cm onto a designated target area, landing on their dominant leg only, and then in similar fashion to Lam and Valovich McLeod[41], jump to maximum vertical height. Results indicated that the female population trended towards a stiffer lower extremity with reduced dexterity. Contributing to joint stiffness, females demonstrated a muscle activation pattern including notable co-contraction of the musculature surrounding the knee and ankle joint. The current study did not find any significant differences in lower extremity joint angles between genders during a jump-landing task. Overall findings support the notion that females may be at increased risk for ACL injury due to stiffer landings. In conjunction with Russell et al.[16] and Decker et al.[40], Lyle et al.[42] proposed the idea that lower extremity musculature is pre-activated prior to landing which may contribute to the 'stiff' landing patterns observed in females.

Again using a population of collegiate level athletes as in Lam and Valovich McLeod[41] Lephart et al.[43] sought to examine gender differences in lower extremity biomechanics during a forward-hop task including analysis of kinematics, GRF and strength. Fifteen female athletes participating in Division I level athletics including basketball, volleyball, and soccer, whom were also deemed in good health, were matched with 15 additional healthy male participants to form the subject population. Subjects were required to perform two different landing techniques: a single-leg landing and a forward hop. During the single-leg landing task, subjects landed on an indicated target on a force plate with their dominant limb only, landing from a height of 20cm. For the forward hop task, subjects began at 45% of their height away from the targeted landing area on the force plate with an 'obstacle' located halfway between the two. Strength data was collected via use of the Biodex System III Dynamometer. During both landing tasks, results indicated that females landed with a more extended knee yet with no significant difference in GRF when compared to their male counterparts. Another trend noted in the female population was a lesser amount of time to reach 'maximum angular displacement' at the knee which indicates that females may land in a more "abrupt" fashion. Lastly, isokinetic testing revealed that females had lower relative strength in the quadriceps and hamstrings which has implications on landing patterns and force attenuation. Therefore, in combination, researchers cite the observed landing patterns of females in this study to be in agreement with commonly held beliefs regarding non-contact mechanisms of ACL injury.

Many other studies examining gender differences in lower extremity biomechanics have chosen to study multiple different types of tasks during the course of one research study. Pappas and Carpes[44] studied 28 recreationally active, healthy subjects (13 male, 15 female) for the purpose of examining gender differences in lower extremity kinematics during the course of two different jumping protocols. Researchers required that as part of being ‘recreationally active’, subjects must have been participating in an athletic activity that exposed them to regular jump-landing activities. Subjects were rendered ineligible to participate if they had received any form of prior landing technique training. During the course of the study, subjects performed two different landing protocols in a randomized fashion: (1) maximum bilateral forward jump-landing at a distance 20cm from the designated force plate and (2) bilateral drop landing from a box 40cm in height. Results revealed both a difference in lower extremity symmetry when comparing genders as well as when comparing tasks performed. With analysis of gender differences, results varied according to the task. For the forward-landing, females had greater knee valgus asymmetry. For the drop-landing, females had greater ankle abduction, defined by the researchers as “navicular drop” and “subtalar pronation”, asymmetry. When comparing across the given task performed, kinematic analysis indicated a greater overall asymmetry when participants performed a forward landing task, specifically knee valgus and hip adduction. Therefore, this indicates that task specificity may matter in regard to landing kinematics and gender differences. Results also demonstrated that overall, both genders tended to have greater asymmetries with frontal plane motions in comparison to the sagittal plane. Anatomically, musculature in the lower extremity is oriented in a way to primarily absorb shock in a sagittal plane motion, while frontal plane shock absorption primarily relies on “inert structures”, including ligaments. Secondary to the asymmetries noted during analysis, authors cite that their findings give further validation of the leg dominance theory involved in increased ACL risk in the female population. Significant asymmetries during landing can lead to detrimental effects to both limbs as it is proposed that one limb has to unequally distribute the landing forces while the other limb may become "de-trained" as a result of bearing less load. One plausible reason that researchers cited for the cause of the asymmetrical differences in gender is rooted in a motor coordination difference.

Weinhandl et al.[45] also examined gender differences in lower extremity mechanics under various landing techniques, in this case examining landing from different heights. Forty-one subjects (20 male, 21 female) between the ages of 18 and 30 years old, defined as 'healthy' and 'recreationally active' participated in the study with the purpose of determining gender differences in landing patterns from various heights. Inclusion criteria required that individuals be free from current or recent lower extremity injury as well as being free from prior surgery in the lower extremities. Methods required subjects to complete maximum countermovement jumps in order to first determine each participant's maximum vertical jump. Subjects then completed 5 single-leg landings from 4 different heights: (1) 30cm, (2) 40cm, (3) 50cm, and (4) max vertical jump height. This study analyzed gender differences at each height as well as patterns in landing mechanics associated with the landing height. Overall, results indicated that genders may respond to landing height changes with different biomechanical adjustments. With an increase in landing height, females demonstrated an "increased peak knee adductor moment" and a decreased "peak ankle plantarflexor moment" while males demonstrated "decreased peak hip abductor moments". Authors stated that these gender differences are consistent with prior research examining dynamic valgus and its association with risk for ACL injury. When females jumped from a height equal to their maximum vertical jump, they also landed with "increased peak knee extensor" moments. This indicated to the researchers that female landing patterns may involve greater recruitment of the quadriceps. Similarly, in regard to ground reaction forces, gender analysis revealed that females land with a greater posterior force regardless of jump height. According to the researchers, greater posterior ground reaction forces, also leads to greater recruitment of the quadriceps, which consequentially plays a role in an increased anterior tibial shift and subsequently, increased strain to the ACL. When examining differences in energetics among genders, results indicated that both genders absorbed most of the energy via the knee while the secondary area of energy absorption for females occurred at the ankle, via the plantarflexors, to a greater extent than for males. According to researchers, relying on energy absorption at the ankle may lead to increased forces being transferred up the kinetic chain, including to the ligamentous structures. The study found that there were no significant differences in knee flexion angles between genders or peak knee adductor moments when landing from height equal to that of their maximum vertical jump. Therefore, this study demonstrates that these sources may not be independent risk factors for ACL injury.

Fagenbaum and Darling[20] also examined gender differences during different jump-landing tasks. Subjects of this study were 14 (6 male, 8 female), healthy, varsity level collegiate basketball players from the University of Iowa. Methods included 3 different jumping tasks: (1) maximum vertical jump followed by forward leap at distance of 25cm with single-limb landing, (2) single-limb drop landing from 25.4cm height, and (3) single-limb drop landing from 50.8cm height. All single-limb landings were performed on the dominant leg. Results indicated that in this cohort of subjects, female athletes landed with the knee in a more flexed position in comparison to the males. In fact, females tended to demonstrate greater knee flexion just prior to initial contact as well as throughout the landing. Landing in a more extended position is typically thought to increase ACL strain as the hamstrings do not have optimal alignment in this position to protect against anterior tibial translation. Results also indicated no statistically significant difference between genders in regard to muscle recruitment during landing, involving primarily the gastrocnemius and quadriceps. Hamstrings activity was found to be highly variable among and between subjects, but again not significantly different between genders. Therefore, this study, unlike Pappas and Carpes[44] and Weinhandl et al.[45], did not find many of the previously held beliefs in regard to ACL risk in the female population to hold true. The authors hypothesized that ACL risk due to landing pattern differences between males and females may be task specific. Previously mentioned results from both Pappas and Carpes[44] and Weinhandl et al.[45] support this hypothesis as landing mechanics were shown to change based on the specific task.

While many studies have chosen to examine the gender differences in lower extremity biomechanics when landing from a jump, other researchers have decided to examine differences when performing cutting maneuvers. One such study was performed by McLean et al.[2] in which they sought to assess differences between genders in regard to lower extremity joint kinematics and GRF when performing sidestep cutting maneuvers with and without a replicated defensive opponent. Sixteen (8 female, 8 male) subjects, with considerable exposure to performing maneuvers similar to those involved in the methodology and without previous history of lower extremity surgery, participated in the study. As participants in the study, subjects were required to perform sidestep cutting maneuvers on a force plate with approximate cutting angles of 30-40 degrees with randomization in regard to the absence of presence of a simulated opponent. Results of the study indicated that females demonstrated less of the following motions: hip flexion, knee flexion, hip internal rotation, knee internal rotation, and hip abduction.

Contradictory to the findings of Fagenbaum and Darling[20], this indicates that females would be at increased risk of ACL tear due to the anterior tibial pull associated with the quadriceps as well as the less than optimal alignment in this position for hamstrings protective capabilities. Authors hypothesized their findings may be due to task and population specificity as well as lower extremity strength differences. Overall, females also demonstrated greater knee valgus angles and tended to cut with a more pronated foot. Due to the fact that females demonstrated a greater knee valgus, and to the researchers surprise, a lower tibial internal rotation angle, it was hypothesized that the position of knee valgus is most important in determining ACL injury risk. Researchers reported that due to the variability noticed in subjects among trials, it can be known that there is a neuromuscular control component associated with landing patterns and is not solely due to anatomical differences between genders. Female participants were noted to have greater variability among trials in regard to rotational mechanics at the knee while male subjects had more variability at the hip. The greater the variability of motion, the greater the likelihood that any given trial could be atypical enough to reach a 'risky' movement pattern. However, researchers also made the point that variability could be seen as a protective quality as it might mean individuals can better adapt their movement patterns. With inclusion of a simulated defensive opponent, lower extremity mechanics responded similarly between genders. Due to the fact that impact of defensive opponent is not within the primary focus of the current study, the details of this portion of the results will not be discussed further. Although their primary focus was to assess gender differences at different stages of development in 156 soccer players, Sigward et al.[4] also examined gender differences in sidestep cutting maneuvers. In agreement with McLean et al.[2] this study also found females demonstrated greater knee valgus angles in comparison to male participants. Based on the presented findings from existing literature, one can see the relative inconsistencies in results as well as the numerous theories that have arisen in regard to gender differences in lower extremity biomechanics resulting ACL injury risk.

Electromyography

The next focus of this literature review is the electromyography (EMG) of the lower extremity between genders while performing athletic maneuvers. Electromyography is used to measure how quickly and to what magnitude specific muscles activate. Electrodes are placed on the subject's clean, smooth skin of the muscle belly that the researcher is interested in. The electrodes send information at different frequencies to the computer during the time interested for the researcher. The most common muscles of the lower extremity for the purpose of studying the amount of strain on the ACL were the vastus lateralis, vastus medialis oblique, biceps femoris, semimembranosus, semitendinosus, medial and lateral heads of the gastrocnemius. However, not all studies include all of the muscles listed above. There have been many studies that have looked at the differences in muscle activation between males and females completing athletic maneuvers. Although there is a large quantity of this research, the exact differences between males and females are still not understood.

Malinzak et al.[8] studied 3-D knee motion and EMG of the quadriceps and hamstrings between male and females during athletic movements. The subjects consisted of 11 males and 9 females who were considered recreational athletes. Researchers defined recreational athletes as "a person who plays basketball, soccer or volleyball less than or equal to three times per week but does not follow a professionally designed training regimen"[8]. Researchers used electrodes on the vastus lateralis (VL), vastus medialis oblique (VMO), biceps femoris (BF), semimembranosus (SM) and semitendinosus (ST). Subjects were asked to perform two 5-sec maximum voluntary isometric contractions (MVC) for both the quadriceps (VL and VMO) and hamstrings (BF, ST, and SM). To test the quadriceps, subjects were placed in a sitting position with the knee flexed at 90 degrees. To test the hamstrings, subjects were placed prone with the knee flexed at 30 degrees. This was done to determine to normalize muscle activity for each subject. The normalized data was then integrated (IEMG) to combine the VMO and VL for the quadriceps and the BF, ST and SM for the hamstrings for EMG analysis. For the cutting and running movements, subjects also had passive reflective markers on the dominant leg that were placed on critical landmarks. The critical markers were sampled at a rate of 240 frames per second by 4 different cameras calibrated for a 1 m long x 1 m wide x 1 m high space. The subject performed 3 trials of each athletic task using their dominant leg for each maneuver. The three tasks were: running, side-cutting and cross-cutting. Subjects were instructed to approach the task with an 8-m run. The running task was simply running forward, with placing the dominant leg in the marked area. Side-cutting was defined as using their dominant leg and cutting 45 towards the non-dominant side. Cross-cutting was defined as using their dominant leg and cutting 45 towards the dominant side. The means and standard deviations of the averaged horizontal velocities at the initial foot contact with the ground and takeoff were determined for each gender in each athletic task. Independent t-tests were conducted to compare the averaged horizontal velocities at the initial foot contact with the ground and takeoff in each athletic task between genders[8].

Data found that between genders with each task there was a significant difference in knee joint flexion-extension motion, valgus-varus motion, and normalized quadriceps and hamstrings IEMG patterns. Females had significantly lower knee flexion angles, increased knee valgus, increased quadriceps activation and decreased hamstring activation compared to men during each task. The knee flexion angle was consistently different between males and females with cross-cutting, with a maximum of 15 degrees at takeoff of foot in the running and side-cutting task. Although females had consistent valgus throughout the movements, males tend to be in valgus during initial contact of the foot on the ground. The quadriceps IEMG was greater in females, especially in the running and side-cutting task. In contrast, the hamstring IEMG was lower for females, especially in the running and cross-cutting task. These findings support other research results that the differences between males and females could be due to anatomical structures, motor control patterns, and physiological differences[8]. This study also supports that females may have knee motion patterns that put them at an increased risk for increased load on the ACL. Earlier studies have found that an increased anterior shear force increases the load on the ACL. Researchers in this study have evidence to support ways that the anterior shear force may be increased in females compared to males, including decreased knee flexion angle and increased quadriceps activation coupled with decreased hamstring activation during these athletic maneuvers.

Garrison et al.[46] compared the root-mean-square (RMS) EMG of lower extremity muscles at initial contact and at peak knee internal rotation moment between genders during drop landings. The subjects consisted of 8 male and 8 female varsity college soccer players. Subjects were healthy, without a lower extremity injury for a year and without an ACL repair on their dominant leg. Researchers placed electrodes on the gluteus medius, biceps femoris, vastus lateralis and rectus femoris with a sampling rate of 1080 Hz. Reflective markers were also placed on critical landmarks for data collection. A force plate was used to calculate mean peak knee moments and raw ground-reaction forces at 1080 Hz, while the video analysis captured the kinetics of the jump. Subjects performed 5 consecutive trials of single-leg landing onto the force plate from a height of 60-cm. The mean of trials was used for analysis. Subjects were instructed to stand on their left leg and drop from the platform "without lunging or jumping" and land on their right leg and keep balance for 2 seconds[46]. EMG data was collected 40 milliseconds (ms) before and 40 ms after initial contact, along with 20 ms before and 20 ms after mean peak knee internal rotation moment. Subjects were allowed practice trials until they comfortable. These trials were not used for analysis. The RMS of each muscle was calculated from the EMG using a 3 ms window with a RMS algorithm[46]. A MANOVA was used to detect gender differences of normalized RMS EMG activity. Post hoc comparisons were calculated using univariate ANOVAs[46].

Results found no significant difference between genders in RMS EMG at initial contact or a peak knee internal rotation moment when all muscles were looked at simultaneously. This suggests that women use a similar landing-control strategy as men, despite increased hip internal rotation at landing (supported from previous research)[46]. The female athletes participating in this study typically perform at a high complexity level and may be trained for this type of task, possibly mastering the correct way to perform without injury. This factor could have led to the finding of no difference for muscle firing between genders for this particular jump-landing task.

Rozzi et al.[47] examined knee joint laxity, joint proprioception, balance, peak torque production time and muscle activity between genders of athletes in functional tasks. Subjects consisted of 17 male and 17 female healthy, collegiate-level soccer and/or basketball athletes. Subjects had no significant history of ligament damage to their knee, no functional deficits in their ankles, and no systemic or vestibular-system disorders. Subjects randomly completed 5 stations for data collection: knee joint laxity, knee joint proprioception, single-legged balance ability, amount of time required to generate peak torque, and reactive muscle activity[47]. The KT-1000 instrumented knee arthrometer was used to measure knee joint laxity. The testing position was supine with legs supported and knee flexed to 20 degrees. Three trials were completed and the mean was calculated. Proprioception was measured using a device that moved the knee into flexion and extension at an angular velocity of 0.5 deg/sec. Subjects were seated and blindfolded with feet in “pneumatic boots inflated to 30 mm/Hg” and with a headset over their ears. Six randomized trials, 3 into flexion and 3 into extension, were performed. The subject was instructed to disengage the device upon detection of movement. To assess single-legged balance the Biodex Stability System, which gives objective data of balance, was used. The device allows for 20˚of surface tilt in 360˚range of motion. Subjects began with the platform level and stable, with measurement of where the foot was placed on the board. The subject was then instructed to maintain balance and keep the platform level while the device was set an instability level of 2 (levels range from 1-6, 1 being most difficult). The amount of time and the degree to which the platform was not level was calculated. The subject performed 3 practice trials and 3 test trials. The mean was calculated from the 3 test trials. Time to peak torque for knee joint flexor and extensor muscles were calculated using the Biodex Isokinetic Dynamometer. Subjects were tested at constant angular velocity of 180 deg/sec with the amount of resistance depending on the torque produced by the subject. Subjects performed 5 submaximal and 3 maximal warm-up repetitions before data collection. Subjects performed 5 maximal test repetitions for data collection. EMG data of onset time, amplitude and area of first contraction subsequent to landing was collected from a landing task from six muscles (vastus medialis, vastus lateralis, medial hamstring, lateral hamstring, and medial and lateral heads of gastrocnemius). Maximal voluntary contraction of each subject was taken by performing a 5 sec single maximal effort isometric contraction. Next, for EMG assessment, subjects were then asked to perform a single-leg landing test. Subjects stood on their test leg on top of a 25.4-cm high landing and jumped to land on the same test leg. The subject needed to maintain balance for 5 sec after floor contact. Each subject had 2 practice trials and 3 test trials. EMG data was taken while the subject was motionless on top of the landing to get baseline activity, as soon as the subject made contact with the floor, and for 5 sec following initial contact. EMG data was collected at 2500 Hz.

Results found that females had greater anterior tibia translation compared to men, indicating greater knee laxity in female athletes. No significant differences were found for time to detect knee motion into flexion between the sexes. Conversely, females took significantly longer to detect knee motion when moving into extension compared to males. Rozzi et al.[47] reason that this could be due to the increased joint laxity in females, so they have a more difficult time detecting when the ligament becomes taut when moving into extension compared to men. Females scored significantly better than men on the single-legged stance test. There was no significant difference found between genders when comparing time to generate peak torque for either flexor or extensor musculature. For the EMG data, there was no significant difference for mean onset times for any of the muscles tested. However, females demonstrated significantly greater peak amplitude in the first contraction and the area that was activated was only the lateral hamstring upon landing compared to males. Studies have found that the activation of the lateral hamstring can protect the knee from anterolateral movement[47]. Researchers propose that the increased lateral hamstring activation in females could be a way to compensate for their increased knee laxity and decreased proprioception into extension. However, this compensatory mechanism may be disrupted with fatigue, leading to increased ligament injury. With these findings, Rozzi et al.[47] support that females may have a different motor control pattern in order to achieve joint stabilization.

Beaulieu et al.[9] compared time-frequency characteristics of the EMG signal and 3D knee kinematics between genders of soccer players completing an unanticipated cutting maneuver. Subjects consisted of 15 female and 15 male elite soccer players and free from any current or previous lower extremity injury. Female athletes were tested between day 2 and 11 (follicular phase) of their menstrual cycle to decrease the effect of joint laxity of the knee. Kinematic data was taken using a seven-camera motion analyses system at 200 Hz in the sagittal, frontal and transverse planes. Subjects wore reflective markers on landmark areas of the body. EMG data was collected on the right (dominant) leg of each individual on the vastus lateralis, vastus medialis, rectus femoris, biceps femoris, semitendiosus, medial and lateral gastrocnemius and tibialis anterior at a frequency of 1000 Hz. The protocol was made up of 3 different tasks: a 45° cutting maneuver, a straight ahead run and a run-stop task. Each task was performed 5 times. A trigger light system was used to randomly determine which task was going to be performed while the subject was completing the approach route, making all of the tasks unanticipated. Subjects were instructed to place their right leg on the force plate to complete the task. Subjects were given 60 to 90 sec between each task to reduce the potential for fatigue. Only successful trials were analyzed. Subjects completed a practice session before the test trial. Researchers were interested in the "cutting cycle" which was defined as" a combination of the prestance and stance phases of the right lower extremity"[9]. To determine if there were significant differences between genders based on Q-angle, 3D kinematics, and EMG variables, one-way ANOVAs were used.

Kinematic results found females had a significantly greater knee valgus angle at initial contact and greater peak knee valgus angles. With this greater knee valgus angle, researchers determined females are putting greater stress on the ACL[9]. The results for EMG data are as follows: no significant differences were found for the semitendinosis or both gastrocnemi during any of phase of the “cutting cycle”. However, males demonstrated a greater frequency at initial contact for the vastii and lateral hamstring firing (BF). Also, males demonstrated a greater frequency for all quadriceps muscle firing during stance phase of the cutting cycle compared to females. The lateral hamstring signal peaked more quickly before initial contact for the females compared to the males. The tibilias anterior peaked significantly later for the females compared to the males. These results lead researchers to infer that females have adopted a different motor unit recruitment strategy at and near initial contact, particularly for the lateral hamstring (BF). With decreased frequency of BF firing at initial contact, this could lead to a decreased ability to stabilize the knee joint, leaving the ACL susceptible to injury[9]. One limitation cited by the researchers was the lack of a skinfold test. Females tend to have more adipose tissue, which could lead to skewed results of the EMG data. However, because the athletes were lean, researchers do not believe this was a major contributing factor to their data. Also, with all other studies, it is impossible to mimic game like maneuvers, but this study came as close as they could to making the tasks random and unanticipated.

Sigward and Powers[10] evaluated the difference in knee joint kinematics, kinetics and muscle activation between genders during a side-step cutting activity. Subjects consisted of 15 female and 15 male soccer athletes competing at least one year at a D1 or D2 collegiate level. Subjects had no complaints of lower extremity injuries. 3D motion analysis was collected using a 6-camera system in all 3 planes. Reflective markers were placed on subject’s bony landmarks. EMG data was collected for the vastus lateralis and medial (semitendinosus and semitendinosus) and lateral hamstrings (biceps femoris) on the right leg at a frequency of 2400 Hz. Subjects completed MVIC to normalize data for each individual. MVIC for the quadriceps was taken with the subject seated (90˚hip flexion and 60˚knee flexion) and instructed to push against a fixed resistance. MVIC for the hamstrings was performed in supine (hip and knee flexed to 30°) with a strap around their hips. Subjects were instructed to perform a single-leg hip bridge and hold for 6 sec. A 6 sec rest break was given between tests. One trial was performed for each muscle group. After MVIC testing, subjects performed 4 trials of a side-step cutting maneuver. Subjects were instructed to run between 5.5 and 7.0 m/s for 5 m before making contact with the force plate with their right foot and then change direction to the left at about a 45° angle. Only trials that matched the indicated speed were analyzed. Subjects were able to practice the protocol until familiar with the approach speed necessary to complete the trials. EMG data collected from the cutting trials were expressed as a percentage of the EMG obtained during MVIC [10]. Differences between genders for any variable within a group was determined using a multivariate Hotelling's T^2 test. One-tailed, independent sample t-tests were used to determine which variable were significantly different between groups, if a Hotelling's T^2 test was found to be significant[18].

Kinematic results show no differences in average sagittal, transverse or frontal plane kinematics during early deceleration between genders. Kinetic results found males had a significantly greater peak knee flexor moment compared to females. Males also showed a larger sagittal plane net joint moment impulse at the knee during early deceleration. Researchers hypothesize that this finding may be due to the muscle activation pattern differences between males and females. Females showed an increase in knee extensor activity, which would decrease the overall knee flexor moment (knee flexor moment=flexor + extensor moments) and decrease the overall moment in the sagittal plane [10]. In the frontal plane, females exhibited a greater initial peak adductor moment (valgus) compared to males, which is an increased peak frontal plane moment. Females demonstrated frontal plane moments that were two times larger than that of males. This can lead to increased load on the ACL, especially when the knee is in a decreased knee flexion angle [10]. There were no significant differences in net joint impulse in the frontal and transverse planes between genders. Overall, this indicates that females generate a different torque at the knee while performing a cut task compared to males [10]. The EMG results found that females had greater average quadriceps activity during early deceleration compared to males. However, there were no significant differences in the average of the medial or lateral hamstrings between genders. The increased quadriceps activation paired with the decreased hamstring activation could lead to an increased anterior shear force, putting more strain on the ligament. However, it is unclear if these would be great enough force to rupture the ligament [10]. Authors state that only a percentage of female athletes demonstrated “at risk” knee motion patterns, while some demonstrated patterns similar to those of men. Researchers also point out that because they were evaluating high level female athletes, they may have already “found appropriate adaptive measures” to decrease their risk for injury.

Myer et al.[11] evaluated the muscle activation strategies between genders when performing a maneuver that puts subjects at a high ACL injury risk. Subjects consisted of 10 females and 10 males who were physically active and did not have a current or a past history of knee injury or surgery. The Q-angle was measured with a goniometer on each subject. EMG data was collected at a frequency of 2000 Hz on the vastus medialis and vastus lateralis. Each subject participated in two separate sessions. The first session consisted of data collection of height, weight, Q-angle measures, gender and age, along with an explanation of the procedure. A normalization EMG was taken in a seated position with instruction to extend the leg with a 20.4-kg to full extension and hold for 5 sec. A resting EMG of the vastus medialis was taken while standing. Subjects stood with feet slightly wider than shoulder width apart and toes pointed slightly outward. The exercise began when the subject leaned to the right by flexing their knee. Once the movement reached 30˚of knee flexion the movement stopped. The subject then returned to starting position with the knee in 0˚of flexion. The timing of the movement was determined by a metronome (2s down and 2s up). Subjects performed 20 repetitions of the side step exercise with 15 seconds between repetitions. However, only data from 4, 8, 12, 16, and 20 repetitions was analyzed. A two-way mixed ANOVA was used for the main and interaction effects, while a post-hoc one-way ANOVA test was used to identify specific interactions. A Pearson correlation coefficient was used to show the relationship between EMG activation and Q-angle.

Results found that there was a significant difference between genders for normalized RMS values. Females had decreased RMS medial-to-lateral quadriceps ratios, along with decreased medial-to-lateral quadriceps activation ratios when compared to males. This means that the quadriceps fire in unbalanced manner, which could contribute to increased knee valgus and increased instability in the frontal plane[11]. There was no main effect of set number on RMS quadriceps ratio, nor was there a significant difference between genders in normalized medial or lateral quadriceps EMG firing. Also, there was no main effect of set number on RMS for either medial or lateral quadriceps measures. Q-angle had no effect on EMG activation, indicating that the angle "did not correlate to measures related to dynamic knee stability"[11]. Researchers suggest that females use a different quadriceps muscular activation strategy compared to males when performing a task that mimics a high risk ACL position. One limitation to this study is the EMG data may not be linearly correlated to force output during interpretation. It is an interpretation of the motor end plate potentials. Researchers suggested that neuromuscular training may reduce the risk of rupturing an ACL by increasing stability by training the motor control patterns at the knee joint[11].

Ebben et al.[12] assessed the magnitude and time of the hamstring and quadriceps activation before and after foot contact during a landing and cutting between genders. Subjects consisted of 12 male and 12 female students between the ages 18-27 years old. Subjects also participated in high-school or college sports and had no lower limb or cardiovascular pathologies. EMG data was collected from the rectus femoris, vastus medialis, vastus lateralis, lateral hamstring and medial hamstring at a frequency of 1024 Hz. During the orientation session, subjects were instructed to warm-up for 5 min on an ergometer and participated in a dynamic warm-up for each muscle tested. Maximum voluntary isometric contractions (MVIC) were performed for both hamstrings (leg curl) and quadriceps (leg extension). Both were performed seated at 60˚of knee flexion. Subjects also performed a vertical jump using a Vertec. The vertical jump height for the test was individualized for each subject for a warm-up and test jump. Subjects also practice an 8-m sprint, which at the end became a 45˚angle cut. This was all performed 72 hours prior to testing to allow the subjects to become familiar with the procedure. For testing, subjects performed 3 trials for hamstring and quadriceps MVICs in a randomized order with a 1 minute rest between trials. The highest of the 3 trials was used. Subjects then performed 3 trials of the jump and cut each in a randomized order with 1 minute of rest between tasks. Subjects were able to practice prior to test trials. These values were averaged and normalized to the RMS EMG of their respective MVIC. Data was evaluated using an analysis of variance.

Results found no gender differences in the magnitude of muscle activation during the precontact phase of the jump or for the cut. This result contradicts previous research, which, according to authors, could be due to the bilateral landing of this study compared to the unilateral landing in most of the previous studies[12]. However, during the postcontact phase of the jump, males had an increased lateral hamstring activation compared to females. Similar to the jump, males demonstrated increased lateral and medial hamstring activation compared to females. This may indicate that males are more hamstring dominant, with females being more quadriceps dominant[12]. For the timing of activation, males demonstrated an earlier activation of the vastus lateralis and medialis during the precontact phase of the jump. No differences were found in the postcontact phase of the jump between the genders for timing of activation. For the cut, there were no significant differences between genders and timing of activation during the precontact phase. Interestingly, females showed a longer duration of rectus femoris and vastus medialis activation during the postcontact phase of the cut. The results of the timing ratios show females had earlier activation of their hamstrings in the precontact phase of the cut. No other significant results were found for the postcontact of the cut or the pre and postcontact of the jump. It may be beneficial for all athletes to participate in training programs that focus on increased recruitment of the hamstrings to potentially decrease the risk of ACL injuries.

Colby et al.[13] studied the qualitative characteristics of the activation of the quadriceps and hamstrings during the eccentric component of high risk ACL injury maneuvers. Subjects consisted of 9 males and 6 females who were healthy and had no prior history of a knee injury. EMG data was collected from the vastus lateralis, vastus medialis oblique, rectus femoris, biceps femoris, semimembranosus and semitendinosus at a rate of 600 Hz. Subjects performed isometric maximum voluntary contractions for both the hamstrings and quadriceps. These maximal tests were performed at 30˚, 60˚ and 90˚. Four athletic maneuvers were analyzed: sidestep cutting, cross-cutting, stopping and landing. Four trials of the running activities were performed at 75% of game speed. Three trials of landing task were performed by jumping from a height of 0.4 meters, landing with both legs, and then pivoting to the opposite side. The data was averaged for each task. All of the quadriceps muscles were grouped together, as were the hamstring muscles. Camera analysis started before the foot stuck the ground and stopped when the subject left the plane of the camera. Researchers were mostly interested in sagittal plane data and more specifically the eccentric movement of the quadriceps.

Qualitative results showed an increase in quadriceps activity during foot strike with all of the maneuvers. However, the hamstrings also showed increased activity before foot strike during the maneuvers, except with the landing task. The hamstrings also showed a decrease or steady activation at and near foot strike, but minimum activation just after the foot strike. Results also demonstrated an increase in quadriceps activity, peaking at the mid-eccentric component of all the maneuvers. There was a maximum difference between hamstrings and quadriceps immediately after the minimum activity of the hamstring after foot strike and before the peak quadriceps activation in the mid-eccentric motion. With this imbalance of activation, the tibia could displace anteriorly, leading to an increased load on the ACL[13]. The average knee flexion angle for all tasks was below 30˚. Previous research has suggested that this angle of knee flexion allows the quadriceps muscle activation could increase the load on the ACL[13]. Eccentric contraction of a muscle produces a very high force, which could also increase the load on the ACL, putting it in a vulnerable position for rupture.

Besier et al.[14] studied the activation patterns of the surrounding knee muscles during planned and unplanned running and cutting tasks. Subjects consisted of 11 male soccer players with no history of lower extremity injury. Subjects completed four tasks: a straight run, sidestep to 30˚and 60˚, and a crossover cut to 30˚. Each task was performed 10 times, 5 times that were planned and 5 times that were unanticipated, but in a random order. Two sessions were completed for testing, for a total of 80 sessions. To reduce the effects of fatigue, subjects were given one minute between trials. Subjects did not wear shoes during the trials to reduce confounding factors. EMG data was collected at 2000 Hz for 3 seconds on the semimembranosus, biceps femoris, sartorius, tensor fascia latae, gracilis, vastus lateralis, vastus medialis, rectus femoris, medial and lateral gastrocnemius. EMG data was normalized to the running data during the weight acceptance and peak push-off phases because these points have the greatest load on the knee. Three different repeated measure ANOVAs were used to analyze the data for this study. The first analyzed the differences in muscle activation across tasks, phases and anticipated knowledge. The second looked at the differences of medial versus lateral muscle groups between tasks and anticipation knowledge. Last, the study analyzed the differences in hamstring ratio across tasks, phases and anticipation knowledge.

Results demonstrate that during a planned condition, selective activation occurred with medial/lateral and internal/external rotation muscles, along with co-contraction of the sagittal plane musculature to stabilize the joint. However, during the unanticipated condition, a more generalized co-contraction strategy was used. With these results, it suggests that the CNS can prepare for a known task and activate the necessary musculature to prevent certain forces that have been learned through certain experiences. With the unanticipated task, it activates a more general contraction of musculature, which may increase the load on the ACL with specific types of movement[14].

Sell et al.[48] studied the neuromuscular and biomechanical properties of unplanned and planned maneuvers between males and females. Subjects consisted of 18 males and 17 female high-school basketball players with no history of severe musculoskeletal injury, or an injury within the last six months, or a disorder of the sensory system, musculoskeletal system or motor system. Subjects were to land with one foot on each force plate, jump off the force plate immediately after in the assigned direction (left, right, or vertical). The last jump was a maximal effort in either of the directions. Subjects completed 5 sets of 6 jumps that were randomly assigned, for a total of 30 jumps. In each set, all types of jumps (planned, unanticipated, left, right and vertical) were completed. Subjects were given at least 30 seconds of a rest break between jumps, and one minute between sets. EMG data was collected for the vastus lateralis and the semitendinosus. EMG data was averaged over all trials. A MVIC was taken for each muscle to be used for normalized data. Subjects also wore reflective markers on critical bony landmarks for 3D collection. Ground reaction force data was also taken using a force plate, one for each foot. For each of the variables, a two-way analysis of variance with mixed-factor repeated measures design was performed. Also, to determine the difference between jump directions and tasks, a post hoc Bonferroni multiple comparison test was performed. Additionally, all variables were analyzed with independent t tests for gender differences.

Results demonstrate many findings with different knee flexion angles for the different types of jumps and the different tasks (planned or unanticipated) performed. These results can be found within each article. However, the focus of this part of the literature review is muscle activity between genders, so the focus was on the muscle activity results. Females showed a significantly greater IEMG for the semitendinosus and co-contraction value (vastus lateralis to semitendinosus) during reactive jumps and jumps to the left. Previous research attributes these results to females compensating to create joint stabilization due to their increased laxity and decreased knee proprioception[47]. Researchers suggest that females use a different strategy to maintain joint stabilization compared to males[48].

Wojtys et al.[15] studied the difference between males and females torsional stiffness when the knee musculature is used, while also looking at knee flexion angles. Researchers performed a power analysis prior to recruiting subjects with the outcome measure of internal tibial rotation.

They found they needed 11 participants in each group. Subjects consisted of 12 males and 12 females D1 collegiate athletes that participated in sports such as: basketball, soccer and volleyball. Another group of non-pivoting sport athletes (bicycling, crew and running) of 15 males and 15 females also participated. Males and females were matched based on age, height, weight, BMI, shoe size, and activity level[15]. Subjects had no previous history of knee or ankle injury. Electrodes were placed on the lateral quadriceps and hamstrings. Subjects were seated with their right foot strapped on a rotating platform. Subjects were asked to relax their lower leg muscles to allow movement in the transverse plane. The foot was struck on the fifth metatarsophalangeal joint by an 80-N force in order to reproduce internal tibial rotation. Subjects also performed the task with maximal muscle contraction with the 80-N force to measure maximal tibial rotation. Test trials were performed with the knee in 30˚and 60˚of flexion. Each test trial consisted of five trials with the leg relaxed and five trials with the muscles active. The foot was placed back into a neutral position at the beginning of trial. Isometric external rotation strength of the tibia with the knee flexed at 60˚was measured. A mirror was used to reflect a laser to measure maximal tibial rotation during all trials. To analyze the data, an analysis of variance with a Bonferroni correction factor was used. This looked at the effects of gender and sport on percentage change in knee joint stiffness. Also, a repeated measure measures analysis of variance was used to look at the effect of knee flexion angle on stiffness between subjects. Two-sided post-hoc t tests were performed to determine magnitude and specifics of the main effects.

Results indicate that females had a significantly greater knee rotation compared to men while performing both the relaxed and active muscle contraction trials. Also, males showed significantly greater knee stiffness than females. Further, the female group of the non-pivoting sports demonstrated more knee rotation compared to any other group during the different angles of knee flexion. However, males that competed in pivoting sports showed a smaller amount of internal rotation during the maximal muscle activation at both angles of knee flexion compared to any other group[15]. Researchers suggest this could be due to the differences in knee muscles, passive connective tissue and soft tissues between genders. From previous research, it is suggested that increased joint stiffness may occur with increased muscle activation surrounding the knee, by compressing the joint[15]. Males in pivoting sports were also found to have a greater amount of percentage increase in apparent joint stiffness with contraction of muscles, while women in pivoting sports were found to have the lowest amount of stiffness. Researchers also found that knee flexion impacted the amount of tibial rotation, with results showing that rotation decreased as the knee flexion angle increased. In general, males demonstrated a greater knee flexor and extensor peak torque compared to females. Additionally, males competing in pivoting sports created the greatest knee and flexor peak torque compared to the other three groups. However, there was no gender differences found with external tibial rotator strength. There were no significant gender differences in maximal passive internal or external rotation of the tibiofemoral joint or in anterior tibial translation.

Effects of Fatigue on Healthy Individuals

Along with biomechanical and muscle differences, fatigue can also play a role into altered knee kinetics and kinematics which would predispose an athlete to an ACL injury. Many studies have examined the effects of fatigue on healthy individuals and how these fatigue effects influence a change in the kinetics and kinematics of the lower extremity. This area is a point of interest for researchers as most injuries occur later in sports activities when the athlete is fatigued, which causes these altered mechanics. ACL ruptures are more likely to occur when a person has poor biomechanics in their activity performance and have a quicker decision-making time. The focus of this part of the literature review is to analyze the effects of fatigue on healthy individuals who have not experienced an ACL rupture or other form of knee injury.

In order to replicate fatigue effects similar to the effects an athlete will experience during a sports game or practice, there are many different fatigue protocols that have the goal of duplicating these effects. The purpose for all of the studies included in this literature review was to analyze how fatigue affected the performance and biomechanics of athletes. Many studies also examined how fatigue influences neuromuscular control during a fatigued state and the need to make quick decisions when jumping or cutting.[22-23,26] Other studies determined how the biomechanics would change during a sidestepping cutting maneuver.[39] One study examined the combined effects of fatigue and drop height on landing kinetics and kinematics from a drop jump landing.[27] Overall, these many components should be added to practice training for healthy athletes.

All studies in this section of the literature review including a pre-fatigue task, fatigue protocol, and a post-fatigue task. Many of the studies examined the difference between the mechanics of the pre-fatigue task as compared to the post-fatigue tasks. Chappell et al.[28] completed one of the earlier studies regarding the effects of fatigue on a healthy individual. The subjects in this study would begin testing by completing a 3-step approach run followed by a 1-footed takeoff and 2-footed landing. Subjects landed on two separate force plates and then completed a 2-footed takeoff for maximum height in one of three directions: forward, backward, or vertical. The three tasks were randomized for each subject. After completing the pre-fatigue task, the subjects moved into the fatigue protocol. This protocol consisted of five consecutive vertical jumps followed by a 30-meter sprint. Vertical jumps were considered successful if the subject maintained 115% of the vertical reach. This procedure was completed until the subject could no longer maintain the vertical jump or was too fatigued. This fatigue protocol was unique in that it recreated both aerobic and anaerobic fatigue that is experienced by athletes during competitions. The post-fatigue task was the same procedure with five vertical jumps between stop-jump trials to maintain fatigue. Results from this study determined that jumping height was significantly decreased for both genders when comparing the pre-fatigue task to the post-fatigue task. Also from pre-fatigue testing to post-fatigue testing, females demonstrated significantly greater peak proximal tibial anterior shear force than males. Other biomechanical changes that were found in this study included females demonstrating a significantly greater knee extension moment at the peak proximal tibial anterior shear force, a significant increase in knee valgus moment, significant decrease in knee varus moment, and a significant decrease in knee flexion. Based on these results, it can be concluded that fatigue is a risk factor for ACL injury due to an increase in strain on the ACL with the above changed knee kinetics and kinematics.

Another study determined how a jump-landing task elicited a fatigue response and therefore altered the biomechanics of a jumping task.[26] Testing for this study included completion of 10 trials of a jump-landing task off a 50 cm platform while landing on two force plates. Immediately after landing, subjects were instructed to jump vertically as high as possible. Each trial was recorded using 3D lower limb kinematic and ground reaction force data. Data from initial contact (IC) and the peak stance-phase values of bilateral hips, knees, and ankles angles were used for analysis to determine when maximal fatigue was obtained. After completing the pre-fatigue testing and measurements were recorded, all subjects participated in the fatigue protocol. The protocol for this study required the subjects to complete 20 step-up and down movements as quickly as possible on a 20 cm step. Next, they performed a series of plyometric bounding movements for a duration of 6 minutes. All jumps were instructed to be from a deep-knee flexion position. Subjects completed these two tasks as many times as possible for four minutes. Post-fatigue testing was the same procedure as the pre-fatigue testing. Results from this study determined there was a statistically significant increase in IC ankle plantar flexion, peak knee abduction, peak knee internal rotation, and peak ankle supination in post-fatigue testing. Female participants demonstrated a greater change in biomechanics when compared to males in all post-fatigue testing. The main goal of the fatigue protocol used in this study was to replicate fatigue similar to that of actual game play, as well as affect limb proprioception by means of less regulated neuromuscular control. From this study, it can be concluded that landing with more ankle plantarflexion-dorsiflexion motion occurred with fatigue. This landing strategy leads to more shock absorption at the ankle and less stress at the knee joint. It is unclear however if there is a correlation between ankle laxity and ACL injury risk and further research should be done to determine these effects.

Following the completion of this study, two follow-up studies were completed to further validate these results. The Borotikar et al.[22] and McLean and Samorezov[23] studies looked to determine how fatigue and the effects of decision-making altered lower limb kinematics during sports relevant testing. These studies were unique in that they incorporated unanticipated trials to the testing procedure and required subjects to alter their jump response last minute. All subjects within these two studies were NCAA Division 1 female athletes. Borotikar et al.[22] included 24 female athletes, and McLean and Samorezov[23] included 20 female athletes. To begin testing in these studies, subjects completed a pre-fatigue sequence of landing tasks. As the subject jumped toward the force plate, one of three lights would activate, informing the subject which jump she was to complete. Options included landing on the left plate and immediately jumping to the right plate, landing on the right plate and immediately jumping to the left plate, or landing on both feet and immediately jumping vertically. A total of 30 randomized anticipated and unanticipated trials were completed. Fatigue protocols in some of the studies included continuous fatiguing tasks while continuing more trials of the pre-fatigue task. Subjects completed five double leg squats between each jumping trial. This sequence was continued until maximum fatigue was completed and the subject could no longer perform accurate trials. The McLean and Samorezov[23] study required the subjects to squat with one of their lower extremities on a scooter to make the task more challenging. Results that were found for both of these studies included significantly greater peak knee abduction, greater knee internal rotation, increase in hip internal rotation at initial contact, and decrease in hip flexion in post-fatigue testing when compared to pre-fatigue testing. Uniquely, the Borotikar et al.[22] study found the subjects to have significant greater peak ankle supination, and the McLean and Samorezov[23] study showed a significant decrease in knee flexion when landing in post-fatigue testing. Peripheral fatigue refers to exercise induced processes that lead to a reduction in force generating capacity of muscles, occurring distal to the neuromuscular junction. Central fatigue is a gradual exercise induced reduction in voluntary muscle activation, occurring proximal to the neuromuscular junction. From this study, it can be concluded that central fatigue occurs faster than peripheral fatigue as demonstrated by the inclusion of unanticipated trials. Fatigue and quick decision-making integrate to make a higher risk for an ACL injury when landing from a jump, particularly when the task is unanticipated. By incorporating unanticipated trials into the study, it is easier to compare an actual sports game where many last minute decisions are made.

Based on the previous studies, it is evident that fatigue protocols altered a change in lower extremity biomechanics. Most of the fatigue protocols were short in duration but high in intensity. The next study determined the effects of a longer fatigue protocol when subjects completed sidestep cutting maneuvers.[39] To begin testing in this study, subjects participated in a 20-meter shuttle run test to determine exhaustion speed or an approximate VO_2 max. Next, maximal effort countermovement jumps and sidestepping cutting maneuvers were determined. Finally, five sidestep cutting maneuvers were performed. The fatigue protocol for this study required subjects to complete a 60-minute shuttle run test that is divided into 3-15 minute blocks and 1-10 minute block, with a 3 minute rest break between each block. Tasks within each of the first three blocks included three walks, one sprint, three jogs, and three cruises. The final block alternated between jogging and cruising. After the fatigue protocol, subjects completed 3 maximal countermovement jumps (CMJ). Following the fatigue protocol, subjects reported their RPE level and then completed the post-fatigue testing, which was the same as pre-fatigue testing. The results of this study did not find any significant peak joint moment differences due to fatigue. A fatigue response was elicited, but the hypotheses of this study were not supported due to no statistically significant findings. Based on these results, it is suggested that a submaximal level of fatigue was reached and therefore fatigue effects were subtler than in previous studies. This fatigue protocol was suggested to be more realistic to a sports activity due to the longer nature, but the results did not support this assumption.

Because there are many options for fatigue protocols that effectively find altered biomechanics of the lower extremity during the fatigued state, one study determined if there was a difference between two protocols: a short duration, high intensity protocol versus a long duration, lower intensity protocol.[24] To begin testing in this study, the subjects were allowed ten minutes of self-directed warm-up consisting of cycling and stretching. Five trials of running-stop-jump task were performed where subjects would run down a runway, jump onto two force plates, and then jump vertically in the air as high as possible as if heading a soccer ball. Subjects would then complete the functional agility short-term fatigue protocol (FAST-FP). This protocol started with the subject completing 20 seconds of step-up and step-down movements on a 30 cm box to a beat of 220 bpm. Subjects then completed an L-drill around 3 cones. Next, subjects completed 5 countermovement jumps that reached 80% of their maximum jump heights. Finally, participants ran down and back on an agility ladder at a pace of 220 bpm. Four sets of this protocol were completed with no rest in between. One week following completion of the FAST-FP, subjects returned, completed the pre-fatigue task, and went through the slow linear oxidative fatigue protocol (SLO-FP). In this protocol, subjects began with completing a VO_2 max test. Participants were required to run at 9 km/hr for 5 minutes followed by a 1 km/hr increase every 2 minutes until subject was no longer able to continue running. The subject would then rest for 5 minutes after the VO_2 max test was completed. Subjects then alternated between two running speeds over a 30-minute running time. There were 6 intervals at 70% of the subject's VO_2 max level followed by 1 minute of running at 90% of the VO_2 max level. Once each of these fatigue protocols was completed, subjects completed five trials of the running-stop-jump task as the post-fatigue testing. Results for this study found that there was significantly less hip flexion at all times analyzed during post-fatigue testing. Subjects also demonstrated significantly less knee flexion for post-fatigue testing. Between the two protocols, hip abduction was significantly greater during the posttest of the FAST-FP during peak knee flexion when compared to SLOW-FP post-testing. Also following the FAST-FP, there was a significantly greater internal knee adduction moment when compared to the SLOW-FP. In general, subjects demonstrated a more extended landing position after being exposed to the fatigue protocol, leading to an increased ground reaction force and greater quadriceps muscle activation. This muscle activation is a disadvantage for the hamstring group because there is a smaller angle of pull, which reduces the amount of posterior force that is applied to the tibia, causing more strain on the ACL. Although there were not as many differences between the results from the two protocols, the frontal plane hip and knee changes (increased knee abduction and internal rotation, increased hip internal rotation, and increased hip internal rotation moment) were greater after the FAST-FP. After Sanna et al.[39] determined that a longer fatigue protocol did not elicit as intense of ACL injury risk as a quick duration and high intensity protocol; however, these results were not confirmed by Quammen et al.[24] who found that there was no significant difference between protocols but that fatigue in general increased the biomechanical risk for ACL injury.

After the previously described study by Quammen et al.[24], two studies examined the effects of the FAST-FP on lower extremity kinematics and kinetics while performing stop-jump and sidestep landings[32] and sidestep cutting tasks.[38] These two studies had similar testing procedures. To begin the pre-fatigue testing, subjects completed 10 unanticipated trials, five sidestep trials and five stop-jump trials. To make each trial unanticipated, a light beam would trigger two meters before the subject reached the force plates informing them of which task to perform. A sidestep cutting task required stepping onto the force plate with the dominant foot, and cutting to the opposite force plate. The stop-jump task required the subject to plant one foot on each force plate and then jump into the air as if heading a ball in a soccer game. Cortes et al.[38] included the addition of four unanticipated trials within the fatigue protocol to progress fatigue throughout testing. This sequence was completed until the subject could no longer complete any more trials. The fatigue protocol utilized in this study was the FAST-FP, in which a description of the testing can be seen above in the Quammen et al.[24] study. Post-fatigue tasks were the same as pre-fatigue tasks and results examined the differences between the two testing times. A unique aspect of these studies is the use of heart rate to determine when the subject was fatigued rather than relying on an RPE scale. Another unique aspect to these studies included use of the Landing Error Scoring System (LESS). As described previously, it is a tool that analyzes a person's jump based on demonstration of proper lower extremity biomechanics when landing. Results from these studies determined there was a significant decrease in knee flexion and a significant decrease in hip flexion in post-fatigue tasks. In Cortes et al.[25], there was a significant decrease in knee rotation at initial contact and knee flexion at the peak posterior ground reaction force. The stop jump task also demonstrated a significantly higher sagittal angle change when compared to the cutting tasks. Based on these results, it can be concluded there was an altered landing posture while each subject was in a fatigued stated, regardless of the demand of the task. In the Cortes et al.[38] study, results demonstrated a significant decrease in hip abduction and hip adduction moment. Based on the findings from these two studies, it can be concluded the reduced peak stance knee flexion moment represents an adaptive strategy to ensure a successful landing despite being in a fatigued state. By landing in a more extended stance, there is an increase in proximal tibial anterior shear force due to an increase in patellar tendon shaft angle.[25] This muscle activation is a disadvantage for the hamstring group because there is a smaller angle of pull, which reduces the amount of posterior force that is applied to the tibia, causing more strain on the ACL.[38] Because there were significant results in this study, authors suggested including use of the LESS when assessing risk for ACL injury.

The final article for this section of the literature review studied the combined effects of fatigue and drop height on landing kinetics and kinematics from a drop jump landing.[27] For the pre-fatigue testing, each subject practiced three different drop jump heights from the heights of 0.3, 0.4, and 0.5 m boxes. Subjects were instructed to step off the box, land with both feet on the two force plates and then immediately perform a countermovement jump. Following this, subjects performed maximal isometric contractions to determine quadriceps and hamstring strength. The fatigue protocol for this study consisted of the subject wearing a 6.5 kg weighted vest and performing two-legged squats for 30 seconds with knees flexed to 90 degrees at a pace of 50 beats per minute. The vest was then removed and subjects were to complete 3 maximum vertical jumps at least 80% of their maximum jump height. The fatigue protocol was discontinued when 80% of their maximum jump could not be obtained. Results from this study indicated that knee valgus moment was significantly increased in post-fatigue testing, with females showing a greater increase than males. Results also showed that by increasing the drop height of a jump, the greater the increase in hip and knee flexion at initial contact along with greater vertical ground reaction forces and loading rates. However, this increase in GRF leads to an increased likelihood for ACL injury due to larger internal muscle moment needed to counteract the increase in ankle, knee, and hip motions. Most importantly, results from this study demonstrated a significantly greater increase in knee valgus from pre-fatigue to post-fatigue testing. An increase in knee valgus leads to an increased strain on the ACL and other knee ligaments. This study only incorporated the effects of peripheral fatigue, so only insufficient muscle activation can be the cause for the results. From the results, it is important to incorporate different drop jump heights when training athletes and working to prevent ACL injury as these different drop heights alter the response needed by the lower extremity during a fatigued state.

All of the studies in this part of the literature review showed that changes in the knee kinetics and kinematics indicate an increased strain on the ACL and therefore an increased risk for ACL injury during a fatigued state for healthy athletes. By landing in a more extended position following a jump, there is more strain placed on the ACL. By incorporating unanticipated trials into testing procedures, it is more sport specific and replicates real life fatigue similar to that in a sports game. After analyzing the results from these studies, fatigue affects healthy individuals in a significant manner that increases the likelihood for an ACL injury. The most effective protocol will include the subject being in a fatigued state, will include unanticipated trials to include central and peripheral fatigue effects, and will include various tasks, such as sidestep and different drop heights, to fully produce the effects of fatigue. These techniques should also be included in the training of healthy athletes to lessen their likelihood for an ACL injury.

Biomechanics and EMG of Subjects with ACL Deficiency or Reconstruction

Once an ACL injury has been sustained, it is imperative that the athlete receives correct rehabilitation in order to decrease risk of future ACL injury on the involved or uninvolved leg. Researchers are currently looking at the deficits post ACL reconstruction, including any biomechanical, kinematic, and kinetic differences relating to hip, knee, and ankle motions. The ability to detect significant deficits is crucial to optimize the rehabilitation program before the athlete is safe to return to sport. Establishing gender strength differences plays a helpful role in determining potential reasons for increased incidence of ACL injuries in females. Ahmad et al.[49] studied the effects of age and gender on ligament laxity and quadriceps-to-hamstring strength ratio in a cross sectional study. The study aimed to determine the best time to initiate ACL injury-prevention programs. Subjects were boys and girls ages 10-18 recruited at New York City Soccer Academy camp. Exclusion criteria was applied for prior knee surgery, use of an oral contraceptive, or generalized ligamentous laxity. One hundred twenty-three subjects were grouped into four groups based on a questionnaire: Group 1 (G1) included 24 premenarchal girls;

Group 2 (G2) included 29 girls 2 or more years after menarche; Group 3 (B1) included 38 boys 13 and under; Group 4 (B2) included 32 boys 14 years and older. Subjects then underwent a physical examination for metacarpophalangeal joint angle, thumb-radius apposition, elbow recurvatum, and knee recurvatum to determine ligamentous laxity and possible exclusion from study. Secondly, they performed Lachman's test to determine anterior tibial translation on the femur. Anterior tibial translation was also measured using a KT-1000 arthrometer at 15, 20, and 30 lbs and manual maximum force. Finally strength measurements for hamstrings and quadriceps at 45° and 90° of knee flexion were performed using a dynamometer. A single examiner performed all measurements. For analysis, a single quadriceps and hamstrings strength value was determined by averaging the strength of the two testing positions. Those numbers were used to calculate the quadriceps-to-hamstrings ratio. Additionally, a single KT-1000 arthrometer laxity measurement for each subject was obtained by averaging the manual maximum data for the right and left knees. A one-way ANOVA with post-hoc comparisons was used to assess the effect of gender and maturity groups on knee laxity, quadriceps strength, hamstrings strength, and quadriceps-to-hamstrings strength. An analysis of power found a minimum of 20 subjects per group was needed for a statistical power of 96%. Significant results were shown for decreased laxity in mature boys as compared to the other three groups. Increased maturity also showed significant increases in both quadriceps and hamstrings strength for both boys and girls. Boys showed a greater percentage increase in hamstrings strength with maturity as compared to girls. Looking at quadriceps-to-hamstrings ratio, mature girls had a significantly greater ratio as compared to all other groups. These results demonstrate significant differences in quadriceps-to-hamstrings ratio in mature girls occurring in the perimenarchal period or shortly after onset of menarche. These results could be important in determining the appropriate time to initiate an ACL prevention program. Due to post-menarche girls increasing their quadriceps strength disproportionally to hamstrings strength, it is suggested that a strength program focused on hamstrings be initiated to improve dynamic knee stability for girls after onset of menarche.[49]

Likewise, the goals of a matched case study by Meyer et al.[50] was to determine the relationship of quadriceps and hamstrings strength to anterior cruciate ligament (ACL) injury risk in female athletes. Twenty-two female athletes that suffered a noncontact ACL rupture (FACL) during sports were matched to 88 female controls (FC) at a 1:4 ratio. Comparisons were made using dominant or non-dominant limb, pubertal status, sport, and nearest height and mass. Male controls (MC) were matched at a 1:1 ratio as a secondary comparative control. All subjects underwent previous isokinetic strength testing of quadriceps and hamstrings prior to their ACL injury to participate in this prospective study. Isokinetic strength was measured by a dynamometer with hip and knee flexed to 90 degrees. Subjects were given 5 sub-maximal warm ups at 300deg/sec. Peak flexion/extension torques were recorded from 10 maximal repetitions for each leg. Additionally participants height, weight, and vertical jump height was measured. MX1 vertical jump trainer measured vertical jump height. Subjects were included if the ACL injury was noncontact. ACL ruptures occurred in range of 1-24 months after testing. Descriptive statistics were used to analyze the study population. Due to skewed data, medians and interquartile ranges were reported. A linear mixed model was fitted for each response to compare case-control differences. The matching was considered a random effect. To decrease variability in responses, vertical jump height was added to compensate as a control for various levels of physical capability. The results showed female athletes who experienced an ACL injury had decreased hamstrings strength, but not decreased similar quadriceps strength compared to matched male controls. Furthermore, female athletes who did not experience an ACL injury had decreased quadriceps strength, but not decreased hamstrings strength as compared to males. Similarly, a study investigated gender differences during a dynamic task. The purpose of the study, performed by Claiborne et al.[51], was to determine the relationship between hip and knee strength, and valgus knee motion during a single leg squat. The objectives of the study were to determine: gender differences in frontal plane motion during a single leg squat (SLS); gender differences in hip and knee strength; and the relationship between hip and knee muscle strength, and valgus knee angle during a SLS. The subjects consisted of 15 men and 15 women. The authors performed two experimental procedures separated by one week. The authors evaluated the frontal plane knee movement with high-speed video cameras at rate of 60 Hz, while the participants performed five nonconsecutive SLSs. Participants were instructed to squat to 60 degrees of knee flexion at a demonstrated speed from a standing position and return to the start position. Subjects performed 5-7 nonconsecutive SLSs to ensure use of 3 appropriate trials for data analysis. Accepted trials involved SLS without loss of balance, and squat rate at approximately 60deg/sec. To avoid fatigue, participants were given 2 minutes rest in between each SLS. Subjects were barefoot wearing shorts. Retro-reflective markers were placed over anatomical landmarks. Prior to SLS anthropometric measurements were taken and used with the motion analysis system to calculate joint angles and segment lengths. Second testing session was performed a week later involving isokinetic strength testing of hip abduction, adduction, flexion, extension, internal rotation, external rotation, knee flexion, and knee extension. Following a 5 minute sub-maximal warm up on a stationary bike, and 4 to 5 practice sub maximal practice trials, subjects performed 3 maximal effort reciprocal repetitions for each muscle group and contraction type. The Biodex Isokinetic Dynamometer was set at an angular velocity of 60 deg/sec. Peak torque of each strength test was recorded for concentric and eccentric motion. Joint kinematics were calculated as Euler angles, using coordinate (three-dimensional x, y, z axes) system of the distal segment relative to the coordinate system of the proximal segment for flexion/extension, varus/valgus, and internal/external rotation. Visual feedback from the Biodex monitor was given as well as verbal encouragement to promote maximal effort. The dynamometer resistance adapter evaluated hip motions of abduction/adduction and flexion/extension in a standing position. Hip internal/external rotation and knee flexion/extension were evaluated in sitting. Evaluation of participants included observing standing frontal plane knee position in standing (anatomical position) and an upright single leg stance; peak valgus knee position; and the change in the amount of frontal plane knee movement during the SLS. Gender differences for maximal effort peak torque were measured using newton-meters (N-m), and body mass relative units (N-m-Kg^{-1}). An independent t-test was used to determine gender differences among tests. Factor analysis was also used to detect potential correlations between body mass relative concentric and eccentric peak torques observed during strength testing. A linear regression was performed for each strength variable and each kinematic variable; while a Pearson product moment correlation was used to examine relationships between the strength and kinematic variables. There were no significant findings of gender differences for all measurements of frontal plane knee kinematics. Results for absolute and body-mass normalized peak torque values observed during isokinetic testing demonstrated that men showed significantly greater absolute peak torque for all strength measurements except eccentric internal rotation. Additionally, when normalized to body mass, men generated significantly greater peak torque than women for concentric hip adduction, flexion, knee flexion/extension, and eccentric hip extension. It was found that concentric abduction, knee flexion, and knee extension peak torque were significant predictors of frontal plane valgus motion of the knee during a SLS. Additionally, the Pearson product correlation found a significant, negative relationship between concentric abduction, knee flexion, and knee extension peak torque and frontal plane knee motion indicating individuals with greater strength in these muscles will likely have decreased knee valgus. It was suggested that high loading of concentric and eccentric knee flexion/extension, hip internal rotation, and hip abduction may have a greater role in predicting excessive valgus motion of the knee in the frontal plane.

With a higher incidence in female athletes, especially for noncontact injuries, it is important to understand the risk factors in females associated with increased risk of an ACL injury. The purpose of the study by Hewett et al.[52] was to identify the potential risk factors for females in relation to ACL injury risk. A group of 205 female athletes playing soccer, basketball, or volleyball were screened prospectively via 3D biomechanical analyses before their seasons. Height, weight, and anthropometric measures were taken as well as which leg they considered dominant. Subjects underwent drop vertical jump trials to quantify their knee joint flexion/extension, and adduction/abduction. Subjects jumped off a 31cm high platform with feet positioned 35 cm apart. Subjects were instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms as if they were jumping for a basketball rebound. Three successful trials were recorded for each subject. A successful trial was defined as the subject landing on the force plates, and in view of the high-speed motion analysis system. The force plates collected ground reaction forces (GRF). Twenty five retro-reflective markers were used to cover anatomical landmarks. Athletic trainers submitted weekly team injury reports. Soccer athletes had 7 ACL injuries and basketball athletes had 2 ACL injuries. All ACL injuries over the 13 month period were noncontact. An analysis of variance was used to compare teams, and paired t tests were used to compare differences between limbs. A Pearson correlation coefficient was calculated for measures of relative correlation between parameters. All neuromuscular, moment, and force variables were introduced into a logistic regression model for injury. Results showed significant differences in knee abduction angles between uninjured and injured ACL groups. The ACL injured group showed an 8.4° greater knee abduction angle at initial contact (IC), and 7.6° greater at maximum knee flexion. Anterior cruciate ligament-injured athletes had a 2.5 times greater knee abduction moment, and 20% higher GRF. Stance time was shorter by 16% indicating motion, force, and moments were occurring quicker. Knee abduction moment predicted ACL injury with 73% specificity, and 78% sensitivity. Dynamic knee valgus demonstrated a predictive r^2 of 0.88. The results indicate that knee valgus and abduction during knee loading when landing are good predictors of ACL injury.

Based off risk factors mentioned in the above studies in combination with other study results, a prevention program was developed for athletes to decrease risk of ACL injury. Gilchrist et al.[53] used a randomized controlled trial to study if using an alternate 30 minute warm-up to enhance neuromuscular and proprioceptive control in athletes would reduce number of ACL injuries, specifically noncontact ACL injuries in NCAA Division I female soccer athletes. Their study was based off a pilot program that had an 83% reduction in ACL injuries in the first year, and 74% reduction in the second year of the pilot program. The program they evaluated is called Prevent injury and Enhance Performance (PEP) created by an expert panel from Santa Monica Orthopedic and Sports Medicine research Foundation to reduce risk of ACL injuries in normal training scenarios without use of specialized equipment. This program involves warm up, stretching, strengthening, plyometrics, and sport-specific agility exercises, which focuses on addressing potential deficits of strength and neuromuscular coordination of muscles stabilizing the knee joint. The program aims to enhance biomechanics when an athlete is fatigued.

The program was tested on Division I women soccer athletes. All Division I women soccer NCAA teams were invited; however teams were ineligible if they had prior participation in the pilot study. Teams whose athletic trainers (ATs), coaches, and athletic director agreed to participate were enrolled in the study. Teams were then randomized, and completed consent form and questionnaire addressing demographics. Intervention teams were instructed to complete the PEP program 3 times per week, and control teams were to perform warm ups as usual. The PEP program consisted of elements addressed above, while also including a video showing high-risk positions to avoid. The video gave both correct and improper form of the exercises they were to perform. The intervention teams were also given replacement exercises to avoid boredom. Coaches and AT's were asked to emphasize technique and provide direct feedback to the athletes. The program was initiated in August at the start of the soccer season and used throughout the 12 weeks of the regular season. Participation and injury reports were submitted by the AT weekly. A knee injury was defined as any injury taking a player out of practice, and requiring medical care causing the athlete to miss one or more days of training. The study considered a knee injury an ACL injury only if confirmed by MRI. ACL injuries were classified into contact or non-contact based on AT's report of the incident. Surveys were provided, and observational visits to 8 teams were done to assess the intervention teams implementation of the program and to observe any similar components in control teams warm ups. Lastly, ATs from all teams, with input from coaches and strength trainers, were asked to complete a survey regarding training drills covering use of common proprioceptive and neuromuscular training drills, including those addressed in the PEP program. Data was entered into an Access database and analyzed using SAS version 8.2 using an as-treated analysis. Eight of the intervention teams were excluded as they did not meet the required use of PEP 12 or more times.

Diversity was demonstrated by 61 teams that completed the study, with each region being represented by 10-34% of teams. A total of 1435 athletes participated with 852 on 35 control teams, and 583 on 26 intervention teams. Medial collateral ligament injuries represented 35% of each group's' knee injuries. Second most common were meniscal or cartilage injuries. The greatest difference was in ACL injury rates, especially non-contact injuries. Though it was not a significant finding, it showed a 3.3 times less injury rate or 70% reduction rate in the intervention group of non-contact ACL injuries. Overall ACL injury rate was reduced by 1.7 times or 41% in intervention group, though still not a significant finding. During the first six weeks of the season, ACL injury rates were similar. However, in the last six weeks, there was a statistically significant decrease in noncontact ACL injuries in the intervention group as compared to the control group, which may indicate that the program is more effective after a certain duration. The results demonstrate that the PEP program is effective in reducing ACL injury risk during regular practice time without need for extra, specialized equipment. It was also suggested that it may take several weeks for an athlete to demonstrate neuromuscular changes in strength, balance, and proprioception. They hypothesized the effects of the PEP program were more effective in the later season, and that contributed to the decreased non-contact ACL injuries in the intervention group. Additionally the PEP program was designed to prevent non-contact ACL injuries, but may have a positive effect on contact injuries due to increased strength and agility.

In determining the best prevention protocol, the most efficient ways to improve lower extremity biomechanics need to be considered for high intensity dynamic activities. The purpose of the Myer et al.[54] study was to determine the biomechanical differences in balance training versus plyometrics at the hip, knee, and ankle motions during landing. The hypothesis was that the balance training would result in decreased coronal plane movement, while plyometrics will not affect coronal plane movement. Subjects were 18 high school female athletes participating in 18 training sessions throughout 7 weeks. The plyometric group consisted of 8 females, while the balance group had 10 females. Lower extremity kinematics were analyzed during the drop vertical jump and the medial drop landing using 3D motion analysis techniques before and after the training sessions were completed. Subjects were marked with 37 retroreflective markers. The drop vertical jump was from a 31cm box, and subjects were instructed to jump off the box then jump as high as possible with both arms up in the air. Two force plates were used, and three successful trials were recorded for each subject. Next, subjects were instructed on the medial drop landing. They were instructed to balance on one leg on a 13.5cm box positioned adjacent to the force plate, and drop off the block medially from the stance limb, land on the same leg, and hold the landing. Three successful trials were collected. Data was collected by 8 high-speed video cameras. Each training session was 90 minutes; with a five-minute warm up consisting of agility ladders. A resistance training protocol was used in conjunction with both groups. Feedback was frequently given to all athletes. The plyometric group focused on jumping movements with maximum effort and power and performance of cutting techniques with quick reactions and maximum effort. Athletes were instructed to perform exercises with the least amount of valgus possible. During quick reactions, athletes were instructed to decrease valgus and focus on proper positioning of knee and ankle to improve efficiency and speed. Exercises were progressed by increasing the complexity and by adding single-leg tasks. In comparison, the balance group underwent a program emphasizing dynamic stability and balance. Athletes were instructed to decrease valgus and to decrease the landing forces in the sagittal plane flexion.

Exercises were progressed by changing from stable to unstable surfaces, perturbations, increased weight, or using single-leg movements. In addition this group performed dynamic balance exercises focused mainly on strengthening the core musculature. Statistical analysis was performed for each 3D motion analysis trial to determine initial contact and peak stance phase values of each lower limb kinematic parameter. Statistical means and standard deviations were calculated. A mixed-design repeated measures analysis of variance was used to test for the main effect and interactions of training, training group, and side (dominant or non-dominant limb) on the dependent variables of the hip, knee, and ankle in the coronal and sagittal plane during the drop vertical jump and medial drop landing. During the drop vertical jump, results showed both plyometric and balance training protocols significantly decreased initial contact maximum hip adduction angle and maximum ankle eversion angle. Additionally plyometric training demonstrated an increased initial contact knee flexion and maximum knee flexion angle during the drop vertical jump test. The medial drop landing showed both groups significantly decreased initial contact maximum knee abduction angle. Furthermore, the balance group increased maximum knee flexion during the medial drop landing. Both plyometric and balance training should be included in an ACL prevention protocol as they affect valgus measures and sagittal plane movements in different ways.

In the same way, the most effective training program to improve neuromuscular characteristics as a whole need to be considered in an ACL prevention program. The Myer et al.[55] study aimed to observe the effects of a comprehensive neuromuscular training program of measures of performance and lower-extremity biomechanics in female athletes. They hypothesized that significant improvements in measures of performance such as vertical jump, single-leg hop distance, speed, bench press, and squat would be associated with improved biomechanical ROM and decreased knee varus and valgus measures shown to be related with knee injury. Subjects included 53 female athletes from Cincinnati high schools and were asked to list their sport. The untrained control group consisted of 12 subjects and the training experimental group consisted of 41 subjects. Subjects underwent a pre-test 1-week prior to the initial training session, and a post-test seven weeks later. The vertical jump height testing was measured on a MXI vertical jump trainer calibrated to each subject. Subjects stood 30.5 cm behind the MXI with the ball attachment and were instructed to jump with both feet off the ground and grab the basketball with both hands. Once the subjects could no longer pull the ball down after three successive trials, their highest height was recorded. The speed testing involved measuring sprint time using the speed trap II timing system which measures a distance of 9.1 m. The best of 3 trials was recorded. Subjects performed single leg hop and hold distance test in which they were instructed to hop and land on the same leg while holding that position for 3 seconds. The farthest distance was recorded. Given practice repetitions and instructed on correct form, subjects were tested on strength for squat and bench press. Weight was estimated and adjusted until subjects could only perform less than 8 reps. Subjects' 1RM was estimated and recorded based off weight used.

Biomechanical testing consisted of each subject being marked with 19 retroreflective markers and analyzed by 8 digital cameras. Subjects performed a drop vertical jump from a 31cm box. They were instructed to drop directly down off the box and immediately perform a maximum vertical jump, raising both arms. Knee joint flexion/extension, and varus/valgus angles were recorded for 3 successful trials. The training procedure involved various and progressive exercises in the following areas: plyometrics and movement training, core strengthening, balance training, resistance training, and interval speed training. The exercises focused on performing athletic maneuvers in a powerful, efficient, and safe manner with proper technique. Training sessions were 90 minutes 3 times per week with subjects recording sets, reps, and weight. Sessions were followed by 15 minutes of stretching exercises. The training period lasted 6 weeks. Instructors were present throughout training sessions to ensure proper form, and provide feedback. Statistical means and standard error of measurement were calculated for each subject. T-tests were used to compare pre and post test scores. Bonferroni correction was applied to correct for possible overall type I error. Statistically significant results for the training group showed increased predicted 1RM for squats, and bench press. Additionally significant results demonstrated increased single-leg hop distance, increased vertical jump height, and increased sprint time. Furthermore training showed significant increased knee flexion/extension angles, and decreased varus/valgus torques during the landing phase of a vertical jump as evaluated by the 3D motion analysis systems. Control subjects did not show any significant differences during the 6-week training time. Clinical application may consider using neuromuscular training programs to decrease injury risk and improve biomechanical factors during athletic performance in female athletes.

If an ACL injury does occur, it is necessary to identify joint mechanic deficits post reconstruction during rehabilitation. Clarke et al.[56] collected data on dynamic joint mechanics of athletes with anterior cruciate ligament reconstruction (ACLr). Specifically the authors wanted to research knee abduction moments and transverse plane knee motion during a game-specific landing and cutting task in ACLr subjects as compared to healthy subjects. ACLr subjects consisted of 9 males, and 9 females who underwent reconstruction and rehabilitation, and were cleared by their physicians. The ACLr group had to pass the International Knee Documentation Committee (IKDC) and a functional screening test to ensure full rehabilitation of the subjects.

The control group consisted of 9 males and 9 females matched to those of the experimental group with no history of knee injury or lower extremity injury for 6 months prior to testing. Participants completed a warm-up before testing. Limb dominance was assessed and determined. The maximum drop jump height was assessed using the participant's chalked palm during a trial from a 0.30-m bench. 45 retroreflective markers were placed on each participant. Kinetic and kinematic data were collected using Cortex software during maximal drop jump test and unanticipated cutting task using two AMTI force platforms, and six infrared motion analysis cameras. Subjects were instructed to reach a suspended target at the maximum jump height previously recorded. The target acted as a trigger of a directional cueing system, which instructed to the subject upon landing which direction for the 45° run/cutting maneuver. Several practice trials were performed, and 20 trials were recorded. 10 successful trials were recorded for each leg. A trial was considered successful if the participant ran the correct cutting direction, with both feet landing on their respective force plates during the jump land. One minute of rest was allowed to prevent fatigue. Mean differences were calculated between ACLr and control subjects for ACLr previously injured limb vs dominance-matched control limb. As well as mean differences within ACLr participants comparing ACLr reconstructed limb versus contralateral injury-free limb. Calculations were performed via repeated-measures ANOVA for hip and knee joint angles and moments. For the landing phase ACLr patients had increased hip flexion, and transverse plane knee range of motion. During the cutting phase, the ACLr subjects previously injured limb had increased internal knee abduction moment compared with that of the control group. No significant differences were reported between the previously injured and contralateral uninjured limb. These results were from a high intensity, unanticipated task very similar to an athletic situation. They suggest that rehabilitation restores the lower extremity mechanics of the reconstructed limb to be similar to the injury-free limb, but that the mechanics are still not as good as a healthy control. This indicates risk of another ACL injury, or potential for development of osteoarthritis in those who return to competitive levels of sport.

Landing mechanics after ACL reconstruction need to be evaluated along with strength comparisons between limbs to identify deficits and prevent further risk of future ACL injury during sport. Schmitt et al.[57] wanted to examine the effect of quadriceps femoris (QF) strength asymmetry on knee landing biomechanics at the time of return to sport after anterior cruciate ligament reconstruction (ACLr). The ACLr group consisted of 77 subjects that had a primary, unilateral ACL reconstruction, completed their rehabilitation program, were cleared for return to all high-level athletic activities by their surgeon and treating rehabilitation specialist, and intended to return to cutting and pivoting sports on a regular basis. Testing occurred within four weeks of the subjects being cleared. The control group of 47 healthy participants from the community were included if they had no history of low back surgery or surgery in either lower extremity, no history of injury requiring the care of a physician in the past year in the low back or either lower extremity, and reported regular participation in sports with cutting and pivoting tasks. All participants age ranged from 14 to 25, and included both male and females. Quadriceps femoris (QF) isometric maximal strength was tested using a dynamometer in sitting with hips flexed at 90° and the knee flexed to 60°. One practice trial was given, and three maximal trials were recorded. The peak torque was used to calculate the quadriceps index (QI) to determine if any asymmetries existed between limbs. A QI of 100% indicates perfect strength symmetry. The ACLr group was subdivided into strength groups based on a high quadriceps index (HQ) of greater than or equal to 90% (37 subjects) and a low quadriceps index (LQ) of less than 85% (31 subjects). A peak QF force output of greater than 10% side to side limb difference is a common cutoff score that is considered to reflect differences in the capacity of muscle performance beyond measurement error. The peak QF force output is commonly referred to in literature regarding return to sport decision making. To achieve statistical power, 22 subjects were required to be in each group, so the group between 85% and 90% were excluded from calculations, as there were only 9 participants. However all subjects were included in the regression analysis. To measure knee pain and symptoms, participants completed the Knee Injury and Osteoarthritis Outcome Score (KOOS). Only the knee pain and symptom subsets of the five total subsets in the KOOS were used. Motion analysis allowed calculation of knee kinematics, kinetic patterns, and ground force reactions during a bilateral vertical drop jump test (DVJ). A 10-camera motion analysis system was used along with 37 retroreflective markers. For the DVJ, participants jumped off of a 31 cm box landing on two separate force plates and maximally jumped vertically with both hands reaching overhead for a target. Three successful trials were completed for each subject. Kinematic variables observed included peak knee flexion and knee flexion excursion during the landing phase. Kinetic variables observed included peak vertical ground reaction force during landing phase, loading rate, and peak external knee flexion moment during landing phase. Means were used to calculate the limb symmetry index (LSI) for each variable observed. To test for greater limb asymmetries in the sagittal plane knee joint mechanics in the ACLr LQ group as compared to the HQ and CTRL groups during landing phase of the DVJ, a multivariate analysis of covariance was used. Linear regression analysis was used to test if QF strength deficits would estimate knee mechanics during landing. Multivariate regressions were used for kinematic and kinetic factors of interest. Pearson correlation and variance inflation were used to determine that each independent variable could be entered into regression models. Results showed statistically significant greater limb asymmetries in all kinetic and ground reaction force variables in LQ as compared to the HQ and CTRL groups, which included decreased involved limb peak knee external flexion moment, reduced involved limb and increased uninvolved limb peak vertical ground reaction forces and higher uninvolved limb peak loading rates. No statistical results showed any differences between HQ and CTRL groups during landing patterns for any variable. Schmitt et al. demonstrated that QF strength does estimate limb symmetry during landing after controlling for graft type, meniscus injury, knee pain, and symptoms. To optimize return to sports it is important to emphasize that QF strength of the involved leg needs to be similar to the uninvolved leg to prevent higher risk landing patterns.

Overall, research continues to identify gender differences, biomechanical, kinetic, and kinematic factors contributing to increased risk of ACL injury. These articles are recognizing the importance of training and prevention programs to address strength imbalances, and enhance proper form during dynamic tasks performed in sport. The research demonstrates the deficits present after an ACL reconstruction and the importance of proper rehabilitation in addition to identification of any deficits prior to return to sport. Identifying and correcting the many factors that interact leading to an ACL injury, as well as properly rehabilitating patients with ACL reconstruction will help decrease overall risk of ACL injuries.

Fatigue Effects of Reconstructed ACL

The question whether an athlete can return to prior level of activity after an anterior cruciate ligament (ACL) injury has circulated the professional, amateur, collegiate, and high school levels throughout all sports in all countries. The purpose of this literature review was to examine the effects of fatigue on the lower extremity of subjects with anterior cruciate ligament reconstruction (ACLR) by looking at how fatigue affects landing, postural control, and physiological and endurance markers.

When comparing individuals with ACLR to healthy individuals, it appears that fatigue may not affect quadriceps: hamstrings co-contraction or dynamic landing. Lepley et al.[29] conducted a study to compare the effects of fatigue and co-contraction of quadriceps and hamstrings which leads to an increased risk of knee osteoarthritis (OA) between patients with ACLR and a control group. The subjects consisted of 12 participants (7 male and 5 females) who were 7-10 months post ACLR and had no other knee complications, surgeries, or injuries since surgery. The control group had 13 participants (4 males and 9 females).Their fatigue protocol included "repetitive sets of 8 double-leg squats which were interspersed with sets of 3 single leg landings until squats were no longer possible". The landing protocol had patients perform a double leg jump over a 17cm box randomly onto one leg and then complete a laterally directed jump to simulate cutting using force plates and dynamic EMG. Data was collected between the time of initial ground contact to 250 milliseconds after initial ground contact. Their study found that even though the ACLR group had weaker quads pre and post fatigue than the control, there was no difference between groups' quadriceps: hamstring co-contraction and that all participants showed a decline in quadriceps: hamstring co-contraction. Clinical implications for their findings suggest that it is the quadriceps weakness that could be contributing to why patients with ACLR have a higher risk and prevalence of knee OA than healthy counterparts since more force would be going through the joint than being absorbed by the quadriceps. This differs from their original hypothesis that increased risk of OA may not be due to the co-contraction of quadriceps and hamstrings.

Thomas et al.[30] conducted a second study to compare the effects of fatigue on quadriceps strength and activation during dynamic landing between patients with ACLR and a control group and found similar results. The subjects consisted of 17 participants who were 7-10 months post ACLR and had no other knee complications, surgeries, or injuries since surgery. The control group consisted of 16 subjects who are recreationally active and had no previous ACL injury nor have had any leg injuries in the past 6 months. Their fatigue protocol included "repetitive sets of 8 double-leg squats which were interspersed with sets of 3 single leg landings until squats were no longer possible". The landing protocol had patients perform a double leg-jump over a 17 cm box randomly onto one leg and then complete a laterally directed jump to simulate cutting using force plates and 32 retro-reflective markers tracked with 8-camera motion capture system. Angles were collected for sagittal and frontal planes between initial contact (IC) and peak knee flexion (PKF); joint moments were collected at PKF only. Their study found that both groups had a decline in quadriceps strength and central activation ratio (CAR) and that even though the ACLR group pre-fatigue had lower strength than the controls, there was no difference between the groups post- fatigue. The CAR is used to quantify quad strength by taking the maximal voluntary isometric contractions (MVIC) torque/superimposed torque delivered through electrical stimulus. They also found that for knee biomechanics, both groups had smaller knee flexion angles and knee abduction angles pre fatigue compared to post fatigue at IC. However at PKF, the control group demonstrated greater knee flexion than the ACLR group both pre and post fatigue. For the knee flexion moment, the ACLR group demonstrated smaller external knee flexion moments than controls in pre fatigued state only. The control group demonstrated a greater knee flexion moment pre-fatigue compared to post-fatigue. However, there was no difference between pre and post-fatigue for the ACLR group. For knee abduction moment, there was no difference between groups and both showed a decreased abduction angle pre to post fatigue. The findings of this study suggest that neuromuscular fatigue did not influence the groups the same and that the clinical implications for their findings conclude that with less knee flexion and decreased quad strength post-fatigue may increase non-contact ACL injury. Even though the ACLR showcased altered biomechanics prior to fatigue, they remained unchanged post fatigue meaning that they are at equal risk for ACL re-injury no matter if they are fatigued or not. While the control did not showcase altered biomechanics until following fatigue, which may indicate their level of risk is dependent on the level of fatigue.

Webster et al[31] conducted a study to see if fatigue affected the landing biomechanics in participants with ACLR compared to their uninvolved leg and to a control group. The subjects consisted of 15 males who were 15-19 months post ACLR and had returned to sport (9 football, 2 basketball, 1 soccer, and 1 volleyball). Their fatigue protocol included a pre fatigue maximum vertical jump height used to mark progression of fatigue throughout the protocol. Subjects performed 5 sets of "10 bilateral squats with arms parallel to the ground followed by 2 vertical jumps and 10 drop landings. If the subject was not fatigued, the number of squats was increased by multiples of 10 until fatigue was reached (jump height reduced by 20% or subject was no longer able to continue)". Subjects reported fatigue on a 0-10 scale after every set. For this study task, participants performed 5 single leg drop offs for each leg from a 30cm box onto the same leg with hands on hips. Retro reflective markers were used along with 10 infrared-sensitive cameras and force plates. Data was collected between the time of initial contact (IC) and 100ms after IC. The study found that there was a "significant decrease in peak hip flexion and ankle dorsiflexion (DF) angles and an increase in hip and knee abduction and internal knee rotation when comparing the involved ACLR to the control group". When comparing the involved to the uninvolved side, only hip abduction, internal knee rotation, and ankle DF were significant. From baseline to 50% to 100% fatigue there was significant difference, however there was no significant difference between 50% to 100% for all variables except ankle DF. Fatigue did not affect variables at IC except for hip flexion which was significantly greater for the involved than both the uninvolved side and control group. For kinetic parameters, a significant decrease in knee flexion, internal and abduction moments was seen by all groups between the 50% and 100% fatigue. The involved leg had a significantly smaller knee moment than the uninvolved leg however there was no difference between the involved leg and control group. The hip flexion moment, it was significantly increased for the involved leg and significantly decreased in the control group. Clinical implications for their findings suggest that even though there was significant difference found, the magnitude was small and may not be clinically relevant and does put one group at a higher risk than the other. However, certain biomechanical landings can put the knee at a higher risk of ACL injury or re-injury. Thus, according to the findings of this study, fatigue does not affect individuals with ACLR differently than healthy individuals when looking at dynamic landings or quadriceps: hamstrings co-contraction.

Other studies have found that fatigue does affect individuals with ACLR; which include balance and hip biomechanics. Frank et al.[32] conducted a study that focused on how fatigue affects postural control and hip biomechanics in females with ACLR performing single leg balance and double-leg jump landing. The subjects consisted of 14 physically active females who were 3-11 months post ACLR surgery, exercised at least 3x per week for 30 minutes and were cleared by a physician. Their fatigue protocol included “repeated squats at a rate of 25 squats per minute with a weighted barbell (30% of subject’s weight) through a knee flexion range of 0 to 60 degrees. Fatigue protocol was stopped when subjects fell 4 squat cycles behind the 25 squats per minute pace or failed to complete 2 sequential squat cycles". Electromagnetic sensors and force plates were used to collect data. For the double-leg jump landing, a 30cm box was placed half of the subject's height from the force plate. Subjects were instructed to jump as high as possible while completing 5 successful trials. For the single-leg balance, subjects stood on force plate with the involved leg and were instructed to keep eyes closed and hand on hips for 20 seconds for 3 trials. Data for hip and knee joint angles were collected at IC, peak hip and knee joint angles and displacements, and net internal knee and hip joint moments were collected during the loading phase. Postural control data was collected during the first 14 seconds of single-leg balance. This study found that hip flexion at IC significantly decreased from pre to post fatigue while hip flexion displacement significantly increased pre to post fatigue. There was no difference found in peak kinetics when comparing pre to post fatigue. Center of pressure sway speed (COPss) significantly increased from pre to post. Clinical implications from their findings suggest that deficits in postural control may put subjects at higher risk of ACL injury or re-injury and that fatigue increases these postural control deficits along with altered hip biomechanics.

While fatigue does not appear to affect some aspects of functional activities (i.e. dynamic landing and muscle co-contraction) it does appear to affect balance. To see what might have caused these differences to occur, McHugh et al[33] compared quad strength after fatigue in patients 2 weeks before and after (5 weeks) receiving ACL reconstruction and compared it to the uninvolved side. The subjects consisted of 42 participants (29 men and 13 women) who were post ACLR. Fatigue protocol included a 30 second maximal voluntary isometric contraction (MVIC) with hips at 90 degrees and knee at 30 degrees of flexion. Electromyography (EMG) data recorded at the initial and final 5 seconds of 30 second holds. This study found that the pre and post-surgery of the involved leg was weaker than the uninvolved leg however, the post-surgical strength was grossly weaker than pre surgery. Preoperatively the study found, a decreased median frequency (MF) in the vastus medialis (VM). However post-surgery, deficits in the MF for the VM, vastus lateralis (VL) and rectus femoris (RF) were found. Even though there was a significant deficit, difference in MF from the involved compared to the uninvolved, the involved leg did not decline during the fatigue test while the uninvolved did show decline. There was a significant deficit difference in integrated EMG (iEMG), which took the amplitude of the initial and final 5 seconds of the contraction and MF from the involved compared to the uninvolved; however, no correlation could be made to strength pre or postoperatively. Clinical implications for their findings suggest that there is atrophy of fast twitch fibers but not slow twitch, which correlates with loss of strength but maintained fatigue resistance. They suggest ACL rehabilitation should include short burst, high intensity contractions

Snyder-Mackler et al.[34] examined the response of quadriceps to an electrically elicited fatigue for both involved and uninvolved lower extremities with patients who have received ACLR. The subjects consisted of 18 males who were 4 weeks post ACLR and had received aggressive rehabilitative therapy 3 weeks post-surgery. Their fatigue protocol included “40 pps, 13-pulse, electrical trains that were repeated once per second for 3 minutes. The intensity of stimulation was set for each extremity to produce 20% of the MVIC of the uninvolved leg”. Peak force was determined for each contraction for both the involved and uninvolved leg. This study found that there was a significant difference in average MVIC between the involved and uninvolved leg, with the involved being weaker. The rate of decline in force between the uninvolved and involved leg was significantly different, with the uninvolved having a faster decline. Clinical implications for their findings suggest that the involved leg is more fatigue resistant than the uninvolved leg and that the difference in MVIC is due to atrophy of fast twitch fibers. McHugh et al.[33] and Snyder-Mackler et al.[34] found that even though the involved leg was weaker than the uninvolved leg, it didn't affect the physiological response of muscle to fatigue. However some studies showed that there was a difference when comparing individuals with an ACLR versus a matched control group.

Kuenze et al.[35] compared quadriceps function and motor pool excitability after fatigue between ACLR subjects and a control group. Their subjects consisted of 26 participants (13 men and women) who were minimally 6 months post ACLR and were able to complete a 30 minute exercise program. The control group was matched on age, BMI, recreationally active and could not have a leg injury in the past 6 weeks. Their exercise protocol included “30 minutes of continuous exercise including alternating cycles of inclined-treadmill walking (5 minutes of selected pace while incline increased from 1 degree to 15 degrees) and bouts of squats and step-ups of 1 minute”. The study focused on the soleus muscle. Hoffmann reflex (H-reflex), Maximal muscle activation (M-wave) and Volitional wave (V-wave) were collected using EMG along with MVIC. Subjects lay prone with knee flexed to 15 degrees while stimuli were delivered in 10 second increments and amplitudes were collected for H-reflex. While staying in that position, subject performed a MVIC; V-wave and M-wave was collected. The study then compared H-wave:M-wave ratio which is “thought to represent an estimation of the number of motoneurons an individual can activate (H_{max}) compared with the estimate of the total motoneuron pool (M_{max})”. They also looked at the V-wave:M-wave ratio which “includes not only an estimate of reflex activation but also ability of an individual to volitionally activate the motoneuron pool”. This study found a significantly lower knee extension torque and quadriceps central activation ratio (CAR) for the ACLR group compared to the control group at baseline. However when looking within groups pre to post fatigue, the ACLR group had significantly less change in knee-extension torque and quadriceps CAR compared to the control. At baseline the ACLR group had a significantly lower V: M wave ratio than the control group; however no difference was found for the H: M wave ratio meaning the ACLR group reflex motor neuron was not affected but their volitional activation was lower than the control group. However when looking within groups' pre to post fatigue, the ACLR group had a significantly less change in V: M wave ratio than the control group while no difference was found for the H: M wave ratio between groups There was a significant main effect found for both groups with post fatigue scores being lower than pre fatigue scores. Clinical implications found by this study suggest subjects with ACLR respond differently to prolonged exercise than the controls with controls having a bigger decline pre to post fatigue. Even though the ACLR group started lower than the control at baseline, there was no difference found post fatigue.

Kuenze et al.[36] also looked to see if there was a difference between men and women who were post ACLR. Kuenze et al. examined how fatigue affects quadriceps function for men and women with ACLR differently. The subjects consisted of 26 participants (13 men and women) that were at least 6 months post ACLR and were recreationally active. Their exercise program included "30 minutes of continuous exercise comprising of 5 separate 6 minute cycles, including 5 minutes of uphill walking and 1 minute of body weight squatting and step ups". They found that there was a difference between sex, with females having a greater decline in quadriceps function both in maximal voluntary isometric contraction (MVIC) and central activation ratio (CAR). Clinical implications for their findings conclude women being at greater risk for re-injury, increased risk of OA, and reduced activity level than male counterparts due to a greater decrease in quadriceps strength post fatigue.

Hantes et al.[37] conducted a study that focused on differences found in tibial rotation and rotational knee moments pre and post fatigue states in subjects with single or double bundle ACLR with a control group. The subjects consisted of 24 males (12 single bundle and 12 double bundle) who were within 1 year of their ACLR surgery and matched on confounding factors (age, BMI, side effected, return to pre-injury activity). The control group consisted of 10 matched participants with no lower extremity injury. Their fatigue protocol included an isokinetic dynamometer with the hip at 90 degrees of flexion and the knee at 60 degrees of flexion. Subjects performed 5 MVIC for flexion and extension. Fatigue was defined when both of the subject's muscles groups dropped below 50% of baseline torque. Twenty-four retro-reflective skin markers, 10 T-40 cameras and a force plate were used to collect data. The task performed consisted of subjects standing one-legged on the force plate while performing a swing movement with the other leg clockwise or counterclockwise. One trial equaled 5 repetitions of touchdown-swing-touchdown with the knee fully extended while holding onto a vertical bar. Two variables were evaluated, maximal internal-external tibial rotation and maximal knee rotational moment. This study found that there was no significant difference in knee rotational moments between all three groups. For pre fatigue, there was no difference found between all three groups for tibial rotation and moment. For post fatigue, there was a significant increase in tibial rotation in the single-bundle group when compared to pre fatigue and the double-bundle group. The double-bundle group showed no difference pre to post fatigue or when compared to the control group. There was no significant difference in knee rotational moments pre and post fatigue within groups. When comparing rotational moments between groups in the pre fatigue state, the control group had a significantly higher rotational moment compared to the single and double-bundle groups; however no difference was found post-fatigue. Clinical implications for this study suggest that single bundle ACLR patients may be at higher risk for tibial rotational loads that can cause ACL re-injury when fatigued while the double bundle have too little tibial rotation, which can compromise normal knee biomechanical function.

Patras et al.[21] conducted a study to see if there was a relationship between endurance markers (i.e. lactic acid) and local neuromuscular response. The subjects consisted of 14 amateur male soccer players with an ACLR within 6 months. Subjects received all the same rehabilitation protocol and had no clinical evidence of pain. Their exercise protocol included performing a GXT test to find the patient's V02 max and lactate thresholds followed by a high intensity run for 10 minutes. EMG data was collected at the 3rd and 10th minute for 15 seconds and lactate was collected prior to and after the run. Their study found that the intact leg had a strong to very strong relationship between neuromuscular response and endurance markers while the reconstructed leg demonstrated a moderate relationship. Clinical implications for their findings suggest that the reconstructed leg may be at higher risk of impaired physiological response to local muscular fatigue leading to decreased tolerance to sustained high intensity activities.

When looking at the physiological, biomechanical, postural, and gender difference and the effect of fatigue in individuals with ACLR, some studies find opposing findings. However the overarching theme found throughout these articles was that the individuals with an ACLR were weaker on their involved leg at baseline than their uninvolved side or than the control group. However, post fatigue there was no difference suggesting that there was atrophy of the fast twitch (type II) fibers while the endurance (type I) seemed to not be affected from the ACLR surgery and rehabilitation. Because of this finding, many studies suggested including high burst, power exercise to help reduce the loss of the type II fibers.

Landing Error Scoring System- Real Time (LESS-RT)

As aforementioned, due to the relative commonality of ACL injuries, as well as the noted biomechanical differences in genders, it is important to utilize reliable and valid outcome tools to assess qualities that may be associated with increased risk of ACL injury. The Landing Error Scoring System-Real Time (LESS-RT) is a tool that measures 10-different jump-landing characteristics that may predispose an individual to a lower extremity injury [58-60]. There have been a handful of studies that have looked at the psychometric properties of the test in a few different populations. Prior to the LESS-RT, the LESS was used more commonly, which allowed researchers to videotape a jumper's landing and make a more indepth analysis of their characteristics to determine if they were at risk for an injury.

Another study performed by Padua et al. [58] investigated the concurrent validity and reliability of the LESS. Subjects consisted of 1655 males and 1036 females who were freshmen at one of the largest military academies in the United States and were going to be playing competitive sports (either recreational or varsity) at the academy. Subjects did not have an orthopedic injury at the time of the study. Subjects performed a jump-landing task, jumping from a 30-cm high box to a distance of 50% of the subject's height and then immediately upon landing attempt a maximal vertical jump. Data from the jump-landing was taken by a 3D motion analysis, which was considered the gold standard, and 2 standard video cameras (sagittal and frontal plane), which was how to collect data for the LESS. Subjects performed 3 test trials, but were able to practice the task until the correct technique was mastered. Analysis of the jump was done during a replay at a later time. Force plate and knee kinematic data were taken at a rate of 1440 Hz. Electromagnetic sensors were placed on bony landmarks to make it easier to identify the areas during analysis.

For statistical analysis, the LESS was divided into 4 quartiles based on their jump-landing biomechanics. (Excellent ≤ 4, good >4 to ≤5, moderate >5 to ≤6 and poor >6) However, it should be noted that the quartiles are specific to this data set only. A chi-square test was used to determine concurrent validity between groups and between genders. One-way analysis of variance were performed for each lower extremity kinematics and kinetics variable, with group as the between-subject factor [58]. A Tukey post hoc test was performed to analyze significant main effects. Interrater and intrarater reliability was also evaluated.

Results of the study found that females had worse LESS scores than males. There were significant group main effects for all lower extremity kinematics and kinetics variables, except for hip rotation angle at initial contact and hip adduction displacement during stance. [58] There were significant differences in most lower extremity kinematics and kinetics between groups of LESS scores. Poor LESS scores demonstrated "decreased knee and hip flexion angle, increased knee valgus and hip adduction angle, increased internal knee and hip internal rotation moment, increased internal knee and hip extension moment and anterior tibial shear force, and increased internal knee valgus and hip adduction moment"[58]. The interrater reliability ICC was 0.84 and SEM was 0.71. The intrarater reliability ICC was 0.91 and SEM was 0.42, indicating good-to-excellent reliability. However, proper training is needed to reach these levels of reliability with scoring the LESS. With these findings, LESS appears to be a good way to evaluate if the subject has a poor jump-landing technique. The validity and reliability of the LESS to predict ACL injury is unknown and further research is being conducted.

To address the ability of the LESS to identify individuals at risk for ACL injury, a second study conducted by Padua et al. [59] examined the validity of the LESS in identifying individuals at risk for ACL injury in elite-youth soccer athletes. Subjects consisted of 348 boys and 48 elite level girl-soccer players between the ages of U-11 and U-18. All athletes did not have any injuries that inhibited participation in soccer. At the beginning of each season, subjects completed a questionnaire and a movement assessment for 3 years (August 2006 and January 2009). The movement assessment was a jump-landing task and was video-taped in the sagittal and frontal planes to review later. Subjects performed 3 test trials of the jump-landing task. Subjects jump horizontally off of a 30-cm height box to 50% of the subject's height, immediately performing a maximal vertical jump upon landing. Subjects could practice until they felt they felt comfortable. A researcher member checked in with each team weekly to monitor injuries. Subjects that reported ACL injuries filled out a questionnaire for specifics about either an indirect or non-contact injury. Blinded researchers evaluated the videos. The average of the 3 LESS scores was used. T-tests were used to compare mean LESS scores in the injured and uninjured subjects. Receiver operator characteristic curve analyses were conducted to find a cutpoint, and sensitivity and specificity.

Results found that seven subjects sustained an ACL injury, 3 indirect and 4 noncontact. The optimal psychometric properties were set at a cutpoint LESS score of 5.17 with a sensitivity of 86% and a specificity of 71%. However, clinically it is difficult to use decimals when scoring subjects. Researchers used the cutpoint of 5, which kept the sensitivity the same, but changed the specificity to 64%. Researchers caution that the LESS cutpoint be scored differently depending on gender and age and further research is needed to determine the best cutpoint for each demographic. Due to the low ACL injury incidence in this study, the positive predictive value (PPV) was low at 1.4%, where the negative predictive value (NPV) was high at 99.8%. These numbers make sense because the rate of ACL injury is low, even in a high-risk population. So the PPV will always be low and the NPV will always be high [59]. "The risk ratio for a LESS score of 5 or more compared with a score of less than 5 was 10.7". The risk ratio for athletes with a preseason score of 5 or more was 10.7 compared to those that had a score of 5 or less.

There were many factors that were predictive of contributing to ACL injury, however only trunk-flexion displacement and joint displacement were significantly different. The LESS may be effective in identifying athletes who are higher risk for ACL injury and could participate in preventive programs to reduce the risk. The limitations to this study are the small sample size of subjects that had ACL injuries and the athletes in this study were just playing soccer. Also, the LESS scoring is added up from individual specific movement errors to give a single score. It may be more beneficial to have the individual score to identify the movements where individuals were scored lower. It may be easier to address a movement problem with this information, rather than have the whole composite score.

A third study by Padua et al.[60] analyzed the reliability of the LESS-Real Time (RT). The subjects consisted of 24 female and 19 male healthy volunteer freshmen from the US Military Academy. Subjects did not have any injury or pathology that limited their physical activity. Subjects performed a jump-landing task consisting of jumping horizontally from a 30cm box to a length of 50% of the subject's height and then immediately performing a maximal vertical jump. Subjects completed 4 trials, with as many practice trials as they needed prior to testing. Only successful jumps were analyzed. During each trial, the evaluator was looking for different components of the jump. Three evaluators analyzed subjects' landing techniques using the LESS-RT. All were certified athletic trainers with 5 years or more of clinical experience and were previously trained in the LESS video scoring. During a morning session, evaluators 1 and 2 analyzed 24 subjects, while in an afternoon session, 19 subjects were analyzed by evaluators 1 and 3.

To determine interrater reliability, an intraclass correlation coefficient (ICC) and standard error of measure (SEM) used calculated during the 2 sessions. Between evaluators 1 and 2, the ICC was .81 and the SEM was .69. For evaluators 1 and 3, the ICC was .72 and the SEM was .79. Since evaluator 1 was consistent in both sessions, the reliability between evaluator 1, and 2 and 3 combined had an ICC of .79 and an SEM of .76. Although research has been conducted to support the LESS is a valid measure, this study did not assess the validity of the LESS-RT and further research is needed to provide this information. The LESS-RT has similar reliability as the LESS video-scoring system, but the validity of the LESS-RT is unknown. Careful training is needed to ensure high reliability of the LESS-RT.

One study conducted by Smith et al.[3] used the measure to determine the effectiveness of the LESS as a screening tool for categorizing individuals at risk for non-contact ACL injuries. In an effort to do so, researchers recruited athletes at both the high school and collegiate level prior to the beginning of their athletic season. For best results, included subjects participated in sports that were defined as involving athletic maneuvers that could result in ACL injury and thus included: soccer, football, rugby, field hockey, basketball, gymnastics, lacrosse, and volleyball. Researchers were able to recruit a total of 3876 athletes (2021 male, 1855 female) to participate in the screenings. Pre-season screenings were performed and the athletes were tracked throughout sport participation for presence of grade III noncontact ACL injury as determined via input from certified athletic trainers followed by the orthopaedic surgeon, and diagnostic testing including MRI and arthroscopic visualization.

During the screening trials, participants performed three drop vertical jumps (DVJ) with evaluation using the LESS. The DVJ protocol involved a bilateral jump-landing from a box 30cm in height with a landing target at a distance 50% of each participant’s height followed by a subsequent maximum vertical jump immediately upon landing. During the jump task, video footage was collected in both the frontal and sagittal plane. For the purpose of assessing reliability of the LESS, two different investigators examined and scored the video footage to assess interrater reliability. Intrarater reliability was also assessed by having investigators score the videos at two separate time points, one week apart. The ability of the LESS to be used as a predictive tool for noncontact ACL injury was assessed via a logistic regression analysis. Results indicated that ICC values for interrater and intrarater reliability were 0.92 and 0.97, respectively, and was therefore defined by researchers as having ‘excellent’ reliability. Out of the 3876 subjects included in the study, 32 individuals experienced a noncontact ACL injury during the course of the study. Twenty-eight (9 male, 19 female) of those 32 subjects consented to having their data analyzed. Each injured subject was statistically matched with control subjects which resulted in a final n of 92.

Statistical analysis revealed that the pre-season LESS score did not have any significant relationship with resultant ACL injury and therefore it may be concluded, based on this particular study, that the LESS is not an accurate method for predicting ACL injury. One possible limitation noted by the researchers was that based on power analysis, a larger sample size may be needed in order to detect statistical significance and therefore give credence to the use of the LESS for predicting ACL risk. Researchers also indicated that perhaps the DVJ is not the most predictive maneuver for determining ACL injury and that further research should examine if there are other movements more relevant to determining the risk of injury.

Next, a study conducted by Onate et al.[61] evaluated the validity of the LESS in comparison to a 3-dimensional motion-analysis as well as determining interrater reliability between an ‘expert’ versus ‘novice’ rater. For these purposes, researchers recruited 19 female, Division I soccer players whom were free of lower extremity orthopedic injuries or recent surgical procedures. For assessment of landing mechanics via the LESS, subjects completed three trials of a drop landing task which involved performing a bilateral drop jump from a 30cm high box and landing at a target distance approximately 30cm ahead onto a force plate. Subjects were instructed to jump at a maximum vertical height immediately upon landing from the initial drop jump.

Analysis of the jump trials was performed via both 3-dimensional motion-analysis as well as individual rater assessment using the LESS tool. Video footage for purposes of completing the LESS was obtained in both the frontal and sagittal planes. The data obtained from the 3-dimensional motion-analysis was collapsed in a way to allow direct statistical comparison to the LESS data, which is scored as either 0 or 1. In regard to analysis of interrater reliability, two raters with varying experience individually analyzed the video footage and scored the participants using the LESS. One rater was considered an ‘expert’ and was a participant in the construction of the LESS while the other was considered a ‘novice’ and had only received a 1-hr training session prior to the analysis involved in the current study. Raters were allowed to dedicate as much time as they wished towards the analysis of the videos but the average time for analysis was 2-4 min, indicating that the process of analysis even for a novice rater is short in duration.

Results of the study indicated that interrater reliability between an ‘expert’ and ‘novice’ rater in regard to overall scores was considered to be excellent with an ICC value of .835. Individual item analysis for interrater reliability revealed that percent agreement ranged from 65% to 100% with all p-values being significant. In regard to the analysis for criterion validity of the LESS in comparison to the 3-dimensional motion-analysis, results indicated that validity varies on an item-by-item basis with percent agreement values ranging from 10% to 100%. LESS items considered to have ‘excellent’ agreement were: 1, 4, 5, 7, 8, and 10. LESS items considered to have ‘moderate’ agreement were: 3, 9, 11, and 13. LESS items considered to have ‘poor’ agreement were: 2, 6, and 12. Therefore, researchers concluded that the LESS has excellent interrater reliability and that the strength of criterion validity is based on each individual item. One strength of this study is that it indicates that an individual can have 1-hr of training on the LESS and score in excellent agreement with someone that has significantly more experience. Another strength of the LESS as determined by the current study is that the LESS, which is much more cost effective, time efficient, and has an easier method of implementation, had an overall moderate to excellent criterion validity with the more clinically unrealistic method of 3-dimensional motion analysis.

CHAPTER III

METHODS

Subjects

A sample of 20 healthy subjects were recruited for this study, 10 males and 10 females (24.9±3.3yrs; 69±4in; 165± 30lbs). Prior to any testing, subjects were given a consent form and were informed on the potential risks and benefits of this study. Once the subject agreed to participate in the study, each subject was administered a subject intake form including the patient's age, competitive sport participation, history of illness, and leg dominance. To determine leg dominance, subjects were asked which leg they would kick a ball with. Other information gathered on the subject intake form were waist circumference and height, and weight, which were then used to calculate the subject's BMI. Subject exclusion was based on a recent history of an orthopedic injury, positive response to the PAR-Q & You form, and health concerns of the participants. This study has been approved by the St. Catherine Institutional Review Board prior to data collection.

Instrumentation

Three-dimensional joint kinematics were measured using Ascension's Flock of Birds electromagnetic motion capture system (Ascension Technology Corporation, Burlington, VT) and Motion Monitor Software (Innovative Training Sports Inc., Chicago IL). Two Bertec force plates (Bertec Corporation, Columbus, OH) placed side to side were 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). Sensors measured 19.8 mm x 7.9 mm, which allowed precise placement over the bony segments to be analyzed. The electromagnetic sensors were placed on the participant's sacrum, lateral thighs, and proximal lateral shanks. To control for interrater error, only one researcher identified the placement of the sensors on spandex sleeves via Velcro attachment for the thigh and shank. This allowed for consistency of marker placement after the fatigue protocol given the sleeves remained in place during the fatigue protocol. 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 in 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). The reliability and validity of electromagnetic motion capture systems in gathering 3-D movements has been previously documented. [62-63]

Procedures

Kinematic Analysis

Prior to digitizing, subjects donned spandex sleeves with the previously described Velcro attached for proper placement of the sensors. These sensors were placed on the distal vastus lateralis (VL) bilaterally and medial aspect of the mid tibia bilaterally. The fifth sensor was attached at sacral level two using adhesive tape (Figure 1). All sensors were reinforced with Velcro straps to prevent slippage during testing. Bony landmarks of the lower extremity were then digitized using the International Society of Biomechanics (ISB) recommendations for the hip and ankle and Grood and Suntay for the knee for data capture. Location of the hip joint center was determined using the Leardini method [64]. This method is done by placing the lower extremity into five different static positions. The right hand rule for all body segments was used as the global reference system for this study. Positive axes were defined as the following:

posterior to anterior for the x-axis, inferior to superior for the y-axis, and medial to lateral for the z-axis.

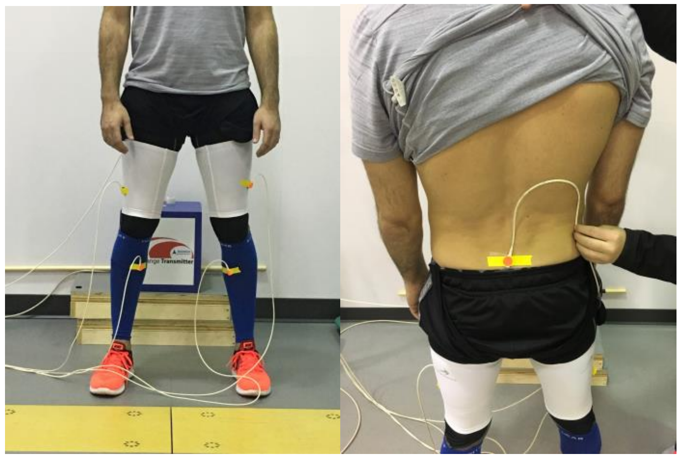

Figure 1. Sensor placement over distal vastus lateralis, medial tibial shaft, and S2 level of the sarcum.

Digitization of bony landmarks of the lower extremity were palpated by one examiner to ensure consistency and marked using a stylus. To determine the local coordinate system of the femur, the lateral/medial femoral epicondyles were palpated and marked. To determine the local coordinate system of the shank, the lateral/medial malleoli and medial/lateral joint lines were palpated and marked. Data was captured at a rate of 100 Hz and with a low pass filter at 30 Hz using a Butterworth 4th order zero phase shift filter. Force plate data was calibrated prior to each subject to limit any error in data collection and was collected at a rate of 1000 Hz.

Athletic testing was completed prior to any data collection. Each subject’s vertical jump height to be completed during the fatigue protocol was determined by averaging three maximum vertical jumps. Maximum vertical jumps were performed by standing next to wall and reaching the right hand as high as possible without jumping. Next, subject’s performed three maximal jumps, starting with both feet on the ground and jumping as high as possible and placing tape on the wall at their peak jump height. An average of the three trials was calculated and was used as a part of the fatigue protocol based on 80% of the average value. Following the maximum jumps, subjects completed between five and eight drop jump vertical jumps. These jumps were analyzed by researchers using the Landing Error Scoring System- Real Time (LESS-RT) protocol. The LESS-RT protocol calls for subjects to jump horizontally out to 50% of their height from a 30-cm box. Subjects were asked to redo a jump if it was not performed correctly. The jumps were analyzed in real time by at least two researchers. Verbal comparison and discussion were used to reach consensus between researchers.

Task

To begin testing, sensors were attached to the Velcro on each spandex sleeve. To reduce slippage, Velcro straps were wrapped around the thigh and lower leg to secure sensors. The sacral sensor was tapped substantially followed by wrapping of a Velcro strap around the waist. All sensor cords were secured using a fanny pack to avoid obstruction of leg movements. Digitization occurred as explained above and participants were allowed 3-5 practice jumps to ensure their technique was adequate. Anticipated and unanticipated trials were included in this study to determine if different motor patterns exist when subjects must quickly adapt to task commands. The jump task required the subject to jump over a 6 inch hurdle with instruction to land with one foot on each force plate and then cut to either the left or right as quickly as possible. The task consistent of four trials of anticipated cutting to the right, four trials of anticipated cutting to the left, and eight unanticipated trials with four to the left and four to the right. Randomization for unanticipated trials was determined prior to testing by lead researcher. For unanticipated jumps, a researcher stood in front of the subject and pointed their arm in the direction required for cutting after the subject initiated their jump over the hurdle. Following the sixteen jump trials, subject's removed sensors while leaving spandex garments on to ensure proper placement of sensors following the fatigue protocol. Following the fatigue protocol, subjects were asked to rate their RPE using the Modified Borg Scale to ensure appropriate fatigue levels were obtained (rating of 8-10). Sensors were reattached to the Velcro on the sleeves and wrapped with the straps immediately followed by jump testing in a fatigued state.

Fatigue Protocol

The fatigue protocol utilized in this study was the Functional Agility Short-Term Fatigue Protocol (FAST-FP). The FAST-FP included four agility tasks to be completed at maximal effort four times: step-up onto a 30 cm-height box, ‘L-drill’, vertical jumps, and agility ladder drills. Figure 2 illustrates the tasks of the FAST-FP. The first task was step-ups onto a 30-cm height box to a beat of 220 beats per minute (bpm) for 20 seconds. Subjects then completed an L-drill around three cones. Cones were placed 4.5 yards apart in the shape of an L. Subjects were required to sprint at maximal effort when completing the L-drill. Next, subjects completed 5 countermovement jumps that reached 80% of their maximum jump heights that was calculated prior to data collection. Finally, participants ran forward (1st and 3rd trials) and sideways facing each direction (2nd and 4th trials) through an agility ladder. Subjects were required to place both feet in each ladder space with every trial. Four sets of this protocol were completed with no rest in between. Encouragement was provided to subjects during the protocol to ensure subjects were working their hardest.

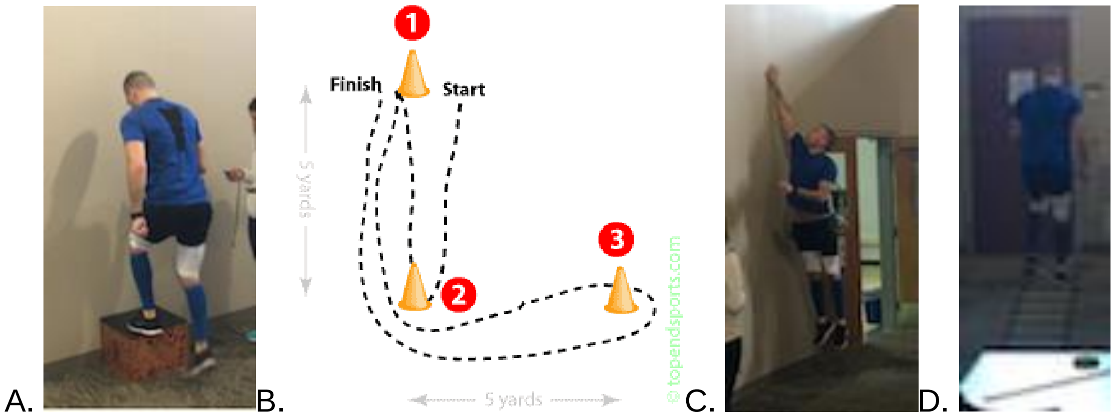

Figure 2. FAST-FP tasks. A. Step-ups onto 30 cm box to a pace of 220 beats per minute (bpm). B. Sprinting through L-drill as quickly as possible. C. Vertical jumps reaching 80% of maximal vertical jump height. D. Agility ladder.

Data Reduction

Raw kinematic data collected by the Motion Monitor system was used, but only the task requirement data was analyzed. Data reduction occurred through the Motion Monitor system by selecting task relevant data based on ground reaction forces (GRF). Time zero started when GRF data was greater than zero and ended when GRF was equal to zero. Data was exported by trial groups as averages and standard deviations for all subjects; i.e. left cut anticipated, right cut anticipated, left cut unanticipated, and right cut unanticipated. Data variables that were exported were pre and post fatigue protocol Euler angles (x, y, z) normalized knee moments (x, y, z) and normalized ground reaction forces (y) for landing. Data was further broken down into pre and post fatigue conditions and placed into a separate column for ANOVA analysis for each condition with pertinent kinematic and kinetic data.

Statistical Analysis

Twenty participants (10 males, 10 females); age 24.9 years ± 3.3 years; height 69 ± 4 inches; weight 165 ± 30 lbs, provided written informed consent and participated in the study. All of the data reduction and analysis was completed by a single researcher to ensure consistency. The independent variables for statistical analysis were gender, pre-fatigue and post-fatigue trials and anticipated or unanticipated trial. The dependent variables included mean and peak knee angles and normalized moments in the 3 planes from the right hand rule as explained previously and normalized ground reaction forces measured by force plates. A three factor repeated measures ANOVA was completed. The between factor was gender; the within factors were pre/post fatigue and anticipated/unanticipated trials. Interaction effects were tested using a post-hoc Tukey test where appropriate. Significance level was determined at a p-value of 0.05.

CHAPTER IV

RESULTS

The results were analyzed for the difference between three main effects: gender, fatigue and anticipation. For each main effect, a separate analysis was completed for each knee. When analyzing the right knee, the participant was cutting to the left and pushing off the right leg (Table 1). When analyzing the left knee, the participant was cutting to the right and pushing off the left leg (Table 2). Data was analyzed during the time between initial foot strike on the force plate and when the foot left the force plate, meaning ground reaction force (GRF) was greater than zero, and then GRF equaled zero. Only significant findings are being reported.

Table 1: Right knee; Cut-side Left. Main Effects ± std dev unless stated otherwise

Gender:	**IR Angle: Mean/Peak**	**Mean ADD Angle**	**Mean ABD Angle**
Male(M)	37.01±9.21 / 50.90±9.73	6.23±6.9	
Female(F)	44.08±10.01 / 60.78±11.51		2.52±15.15
p-value	p=.043/.015	p=.04	p=.04
Fatigue	**IR Angle: Mean/Peak**	**ADD Moment: Mean/Peak**	**Mean Flex Angle**
Pre-fatigue(Pre)	43.57±6.7 / 59.41±8.29	.01±12 /.17±.13	7.88±11.5
Post-fatigue(Post)	37.51±12.13 / 52.27±13.5	.24±.44 / .52±.68	24.09±32.69
p-value	p=.03/02	p=.03	p=.04
Anticipation	**Peak GRF**	**Peak ADD Angle**	
Anticipated (A)	2680	12.17±14.92	
Unanticipated (UA)	2839	10.97±13.91	
p-value	p=.04	p=.02	
Interaction Effects	**Peak IR Moment**	**Peak Ext Moment**	
M+A / M+UA		.05±.04 / .07±.04	
F+A / F+UA		.09±.14 / .08±.13	
p-value		p=.04	
Pre+A / Pre+UA	.08±.03 / .07±.03	0.07±.03 / .06±.03	
Post+A / Post+UA	.07±.02 / .08±.04	.08±.14 / .09±.13	
p-value	p=.04	p=.01	

All values in table were significant.

Table 2: Left knee; Cut-side Right. Main Effects ± std dev unless stated otherwise

Gender:	Peak IR Moment	Mean ADD angle	ABD Angle:Mean/Peak
Male(M)	1.05±.36	12±10.17	NA / 0.47±7.6
Female(F)	1.21±.30		2.12±17.22 / 13.7±17.13
p-value	0.03	p=.00	p=.00/.00
Fatigue	**Mean ER Angle**	**Peak ADD Moment**	
Pre-fatigue(Pre)	43.8±6.23	0.07±.03	
Post-fatigue(Post)	39.2±11.14	.18±.22	
p-value	p=.03	p=.049	
Anticipation	**IR Moment: Mean/Peak**	**Peak ADD Angle**	
Anticipated (A)	.65±.18/1.21±.25	15.46±18.54	
Unanticipated (UA)	.56±.28/1.06±.38	14.41±18.7	
p-value	p=.02/.03	p=.03	
Interaction Effects			
NA			

NA: indicates no significant findings; therefore did not include the value(s).
All other values in table were significant.

First, when comparing genders for the right knee, females demonstrated increased mean (44.08 ± 10.01) and peak (60.78 ± 11.51) internal rotation angles and a mean abduction angle (2.52 ± 15.15). Males demonstrated a mean adduction angle (6.23±6.9).

For the left knee, females demonstrated an increase in the peak internal rotation moment (1.21 ± .30) and increases in mean (2.12 ± 17.22) and peak (13.7 ± 17.13) abduction moments. For males, there was an increase in the mean adduction angle of the left knee (12 ± 10.17).

For the main effect of fatigue on lower extremity biomechanics, the right knee, post-fatigue findings showed greater mean (.24 ± .44) and peak (52 ± .68) adduction moments. A greater mean flexion angle (24.09 ± 32.69) was also noted. Lastly post-fatigue showed a decreased mean (37.51 ± 12.13) and peak internal rotation (52.27 ± 13.5) angles. For post fatigue testing, there was a larger peak adduction angle for the left knee (.18 ± .22). Additionally, there was a smaller mean external rotation moments (39.2 ± 11.14).

For the main effect of anticipation, the right knee demonstrated a decreased peak adduction angle (10.97 ± 13.91) during unanticipated trials. To address the left knee, decreased mean (.56 ± .28) and peak (1.06 ± .38) internal rotation angles were found. Furthermore, there was a decreased peak adduction angle (14.41 ± 18.7) for unanticipated trials.

The only interaction effects involved mechanics of the right knee. First, females demonstrated a higher peak knee extension moment during both anticipated (.09 ± .14) and unanticipated trials (.08 ± .13). Next, participants demonstrated a higher peak knee extension moment post-fatigue for both anticipated (.08 ± .14) and unanticipated trials (.09 ± .13). Finally, a higher peak internal rotation moment was found for post-fatigue unanticipated (.08 ± .14) as compared to the pre-fatigue unanticipated trials.

CHAPTER V

DISCUSSION

The purpose of the study was to analyze lower extremity biomechanics during a jump-cut task, with evaluation of emerging patterns when comparing genders, pre vs. post-fatigue, and anticipated vs. unanticipated scenarios. We hypothesized that riskier biomechanical patterns associated with ACL injury would occur in a fatigued state as well as when jump-cut direction was unanticipated, for both genders alike. When analyzing differences between genders, we hypothesized that a fatigued state and unanticipated scenario would result in significantly greater changes in knee kinematics and kinetics for females, therefore placing them at greater risk for ACL injury.

In regard to the analysis of the results, joint angles and moments must be operationally defined. In the course of the present study, all joint angles were reported in reference to the distal tibia. In review, internal moments counteract gravity's external forces. For example, when a participant landed on his or her leg, gravity wanted to bring the participant's lower extremity into more flexion. To counteract this, a greater internal moment of extension was required to overcome the external force of flexion, which resulted in a more extended position of the knee.

According to our results, the main effects for gender indicated that female's jump-cut mechanics placed them in a position that caused excessive stress on the ACL as compared to males. When combining the results for both right and left knee mechanics, the riskier movement patterns demonstrated by females included increased mean and peak internal rotation angles and moments as well as increased mean and peak tibial abduction angles and moments. This is in agreement with previous research and our hypothesis as previously discussed. Previous research has examined gender differences in lower extremity kinematics and kinetics following completion of various tasks including drop-landing, jump-landing, and sidestep cutting. When synthesizing the research and analyzing the findings in conjunction, multiple studies confirmed the results of the present study in regard to tendencies for knee valgus positioning in females. Studies conducted by Russell et al.[16], Lam and Volovich McLeod[41], McLean et al.[2], and Sigward et al.[4] reported increased knee valgus when comparing the landing biomechanics of females to males. In contrast to our results, multiple studies have reported an increased bias towards lower extremity extension when landing for the female population, which was not a significant main effect of the present study when analyzing gender differences[2,17,18,40,43]. In direct contrast to our results, research conducted by Orishimo et al.[19] and Lyle et al.[42] found no significant differences between genders in regard to lower extremity joint angles when landing. One plausible explanation for this is the influence of task-specificity as well as training background on lower extremity kinematics and kinetics, which is a hypothesis that has been previously proposed [19,20,43,44]. It is important to note that research has supported alternative factors associated with gender differences in ACL injury including anatomic/structural, hormonal, and neuromuscular which, in accordance with the purpose of this study, were not evaluated as primary factors but remain important to consider.

Contrary to previous research and our hypothesis, findings for pre vs post fatigue testing suggest that the movement patterns appear to be less risky in a post fatigue state. We suspect these findings may be due to participants demonstrating a protective mechanism, such as bracing, while in a fatigued state [21-37]. It could be proposed that the subjects were cognizant of their fatigued state, as well as the purpose of the study, and therefore perceived the threat to their body in regard to landing mechanics which contributed to the patient altering their motor plan. Future research will be important in an effort to accurately assess the impact of fatigue with increasing emphasis on standardized and consistent time lapse between the end of the fatigue protocol and completion of the jump-cut task post-fatigue, as this was a limitation of the study.

For anticipated versus unanticipated trials, the results indicated that there was no clear impact on risky movement patterns for ACL injury. One plausible explanation for this finding is due to the variability in timing for indicating the cut direction during unanticipated trials, which will be discussed further as a limitation of the study. This was an unexpected main effect finding and is in disagreement with our hypothesis and previous research, as we projected that unanticipated trials would result in riskier knee kinematics and kinetics [21-37]. This is a topic for continued research as for a more accurate conclusion, it would be beneficial to analyze the impact of anticipation on jump-cut mechanics when employing a standardized and automatic method for indicating cut direction. For exposure to a more realistic challenge and accurate assessment, it may also be important to attempt to mimic a sport scenario as closely as possible (i.e. defensive player).

However, the interaction analysis revealed that female jump-cut mechanics were negatively influenced during unanticipated trials. A fatigued state impacted both anticipated and unanticipated trials. However, only unanticipated trials while participants were in a fatigued state demonstrated riskier movement patterns when compared to pre-fatigue movement patterns. Overall, our results indicated that were was no interaction found between all 3 of the factors that were analyzed. Evidence supports that these 3 factors individually, have been associated with increased risk of ACL injury [21-37].Therefore, we hypothesized that the riskiest movement pattern would include the interaction combination of females, in a fatigued state, during unanticipated trials. Although we did not find an interaction between all 3 factors, components of our hypotheses were supported as previously discussed.

Limitations

There were limitations within our study. First, sample size limits the power of the results. Next, re-digitization had to occur before post-fatigue jump-cuts with 2 participants due to slippage of the sensors following the fatigue protocol. This limitation allowed for potential recovery from the fatigued state, which could question an adequate fatigue level. On a related noted, given that anticipated and unanticipated trials were not randomized as one big group and unanticipated trials were always the last group tested, recovery may have occurred despite doing the task for the anticipated trials. Additionally, unanticipated trials were directed by different researchers so potential variance in timing could have occurred with direction of cuts within each individual and between individuals doing the pointing. Lastly, sensors were attached to a mobile cart and cord whip could have occurred during the task, which may create data capture error.

Continued research needs to be conducted to further address jump-cut mechanisms between genders, fatigue state and anticipation levels. More participants should be studied to increase the power and validity of our results. Attempting to automate direction of unanticipated cuts would be a good addition to help control for variability, especially if based on force plate landing. Randomization of all trials should also be done to similarly influence each condition from a fatigue recovery standpoint. Furthermore, it may be helpful to study more participants with left leg dominance to determine if leg dominance is a contributing factor.

CHAPTER VI:

CONCLUSION

In conclusion, participants demonstrated significant changes in knee kinematics and kinetics. Fatigue and anticipation states influenced knee movement patterns in variable ways, which may indicate an attempt to safely land and cut. Additionally, females demonstrated biomechanics that may increase their risk for ACL injury relative to males. Gender, fatigue, and anticipation conditions had an impact on one another and should be considered when designing sports training programs to reduce risky movement patterns.

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