THE EFFECT OF FATIGUE ON LOWER EXTREMITY MECHANICS DURING THE UNANTICIPATED CUTTING MANEUVER

A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

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MUNCIE, INDIANA

MAY 2013
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May 2013
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The cutting maneuver is a dynamic sports task that allows the athlete to change direction from standing, walking, or running. Running combined with the cutting maneuver increases the strain and places the ligaments of the knee at an elevated risk of injury.1 The sidestep cut is performed by planting with the foot opposite the intended change in direction while the crossover cut is accomplished by planting with the foot on the same side as the intended change in direction.1 The sidestep cut is the more common of the two cuts and is composed of three separate phases: deceleration, plant and cut, and takeoff.1

The deceleration phase of the cut may occur over a few to several running gait cycles beginning with the foot to be planted for the cut. The primary goal during deceleration is to decrease the athlete’s momentum by using the greatest amount of force possible in the shortest amount of time so they can begin to move in the new direction.2 This takes place over a few shortened gait cycles, leading to larger braking forces and increased ground contact time to attenuate the large eccentric forces while placing as little stress on the joints in the lower extremity as possible.2 During the deceleration phase anteroposterior forces are placed on the knee joint causing the posterior cruciate ligament (PCL), capsular ligaments, and the collateral ligaments to tighten in response to anterior translation of the femur relative to the tibia.1 Through an in-vivo anterior cruciate ligament (ACL) strain case study it was found that strain on the ACL increased during the flight phase while the knee was extended and pre-activation of the quadriceps
and gastrocnemius occurred. Though the strain that occurred during the flight phase was not significant, the strain continued to increase during the landing phase prior to reaching its peak at the same time as the peak ground reaction force, and remained high during the stance phase.

The athlete achieves a change in the direction of their momentum during the plant and cut phase with the plant leg providing the chief acceleration force in that direction. During this phase, a large amount of stress is applied medially to the capsular ligaments of the knee. Several studies have indicated an elevated risk for knee injury during the cutting maneuver when flexion, valgus/varus, and internal and external rotation loads act on the knee. The researchers ascertained that external flexion loads when accompanied by greater valgus and internal rotation moments have the strongest influence on the magnitude of stress applied to the ACL. This occurs mainly when the weight is transferred to the stance leg and the knee is near full extension. In a study looking at the correlation between lower extremity posture during initial contact and peak knee valgus moment, the researchers noted that larger peak valgus moments were found in conjunction with larger initial contact hip flexion, internal rotation, and knee valgus, potentially indicating a higher risk of injury. It has also been observed, both in-vivo and in-vitro, that applied valgus or varus moments accompanied by weight bearing, anterior shear force, or quadriceps contraction increases ACL strain. Increased ACL loading has also been identified when knee valgus or varus loading is combined with anterior sheer force of the tibia. The examined effect of combined frontal plane and transverse plane loading has also been considered as these motions have been seen together at the time of ACL injury. Researchers using a robotic arm to look at tensile forces acting on the
ACL found increased forces when valgus loading occurred in tandem with either knee internal rotation loads or external rotation loads. Several authors have sought to refine the ecological validity of their work by using unanticipated tasks to minimize the learning effect, and gauge the kinematic and kinetic alterations made by the subjects when presented with a real-time situation. The use of unanticipated dynamic tasks such as the cutting maneuver is meant to mimic the nature of the tasks’ performances in game situations. Previous research in the area of motor control and the response by the central nervous system (CNS) to anticipated and unanticipated actions indicate that a feed-forward mechanism is used in reaction to anticipated actions or stimuli and that the CNS utilizes a preprogrammed plan for anticipated postural modifications. Essentially, anticipation of a movement can lead to altered reflex responses and postural modifications in order to decrease the impending perturbation and uphold the necessary posture. A previous study discovered that temporal constraints (self-initiated, anticipation-coincidence, and reaction condition) have a significant effect on anticipatory postural adjustments, which are centrally produced as a feed-forward mechanism to offset the mechanical effects of predicted perturbations on stability in dynamic sports tasks. It was noted that the unanticipated reaction condition led to the longest time to complete the anticipatory postural adjustments when compared to the other two conditions. This may potentially correlate to a longer duration of time between unanticipated tasks and postural adjustments to offset the impending stresses incurred during the action.

Joint coordination is another aspect of motor control involved in dynamic movements that is impacted by anticipation. Research observing joint coordination has
indicated that coordination variability provides flexibility in adjusting to perturbations and is central to the alterations in coordination patterns that occur during movement. Thus, if an individual displays decreased coordination pattern variability during an unanticipated task, it is possible that their ability to adjust to the environmental perturbations commonly experienced during a soccer game or practice may be restricted making them more susceptible to potential injury.

In a previous study looking at the anticipatory effects of running and cutting maneuvers on joint loading, the authors found that knee joint moments increased during unanticipated conditions when juxtaposed to preplanned maneuvers. The researchers established that unanticipated maneuvers modified the external moments acting on the knee as a result of the decreased time allotted to generate the proper postural adjustment tactics. It was as a result of these insufficient postural alterations that potentially led to decreased performance of the unanticipated cutting tasks (i.e., decreased cutting angle, decreased speed) and enhanced external loads applied to the knee joint (i.e., valgus, varus, internal rotation, and external rotation loads) in comparison to preplanned tasks.

As an individual performs a motor task(s) they will often times experience some level of fatigue depending on the nature and duration of the task. During higher-intensity, short duration activities, fatigue will primarily occur peripherally. Peripheral fatigue is correlated to the capability of a muscle to perform physical work. As this fatigue occurs, there is impairment to the normal functionality of the nerves and the muscles that are contracting, which translates to a decline in the muscle’s ability to generate force due to the incapability of the body to meet the increased energy demand in the contracting muscles. The most often suggested mechanisms of peripheral fatigue consist of muscle
fiber type and its distribution, the readily available energy supply, the length of the muscle, and the muscle’s strength prior to fatigue. If the task continues at a high level for an extended period the individual may experience central fatigue. At the level of the spinal cord central fatigue results in impaired alpha motor neuron firing or suboptimal rate of recruitment to generate appropriate muscle force. Central fatigue from impaired alpha motor neuron firing can lead to either loss of recruitment or synergistic activation of multiple muscles. The implications for repetitive tasks such as gait are that the overall rate slows and the time it takes to complete the task (e.g., the gait cycle) increases with fatigue.

While both central and peripheral fatigue take place during sustained maximal exertion muscle activity, during sub-maximal exertion peripheral fatigue occurs more often than central fatigue. In the case of a soccer game, it is presumable that while both central and peripheral fatigue will occur for an individual during a game, peripheral fatigue will be a greater factor due to the inherent quick bursts of activity followed by periods of recovery. By utilizing a fatigue protocol that primarily elicits peripheral fatigue, the observations may be more applicable to true sport conditions. Fatigue has also been regarded as a primary component affecting the musculoskeletal system as a result of its connection to diminished proprioception and greater joint laxity and the subsequent reduction in the skeletal muscle’s ability to generate force.

Previous studies looking at the effect of fatigue on various sports tasks have utilized different protocols to simulate game fatigue. This has led to inconsistent findings regarding joint dynamics during these tasks. Some studies have noted a significant decrease in knee flexion after fatigue, where others have not observed fatigue effecting
maximum knee flexion\textsuperscript{6}. The variation in fatigue protocols likely contributes to the incongruous mechanical observations of the knee joint during the sidecutting maneuver\textsuperscript{35}. The two main types of fatigue protocols used to study the effect of fatigue on neuromuscular control strategies are short-term and long-term\textsuperscript{36,37}. Short-term protocols used to stimulate fatigue may include a series of explosive tasks including vertical jumps and sprints, squats and jumps, and single leg squats, whereas some long-term protocols have utilized 60 minute shuttle runs and prolonged intermittent shuttle runs involving periods of walking, jogging, running, and sprinting repeatedly for 60 to 90 minutes\textsuperscript{38,39}. In a previous study, both short-term and long-term fatigue protocols elicited altered hip and knee kinetic and kinematics during sidestep cutting in female soccer players, and, after only five minutes of performing either protocol, mechanical changes in the lower extremity took place that could elevate the athletes risk for injury\textsuperscript{40}.

Previous research has also assessed lower-limb dominance related to the risk of ACL injury and athletic performance\textsuperscript{41-43}. Though there have not been significant findings with respect to limb-dominance and injury risk, several of the authors have stressed that limb asymmetries should be monitored and addressed as these differences can pre-dispose athletes to athletic injury\textsuperscript{41,42,44}. Research by Ross et al., comparing biomechanical variables between dominant and non-dominant limbs found that the dominant limb had greater thigh strength, greater knee flexion range of motion, and enhanced proprioception. Thus, by identifying kinetic and kinematic differences, pre- and post-fatigue between limbs may enhance our knowledge and abilities to design preventative techniques for training, rehabilitation, and conditioning\textsuperscript{45}. 
An additional factor related to knee, and more specifically ACL injuries is that of gender. In comparison to males, female athletes have been shown to be four to six times more prone to injure their ACL\(^{46}\). When performing the sidestep cutting maneuver, women have been found to have decreased hip flexion and abduction, and larger internal rotation when compared to men, predisposing them to a potentially higher risk of injury\(^{47}\). Additionally, women have been found to have less coordination variability during an unanticipated sidecutting task\(^{48}\). A reduction in the variability of intra-limb couplings suggests a more rigid coordination pattern, which could lead to an increased risk of lower extremity injury\(^{20}\). The authors determined that the gender differences in lower extremity coordination variability, predominantly observed in the initial loading phase of an unanticipated cutting maneuver, might attribute to the greater incidence of noncontact ACL injuries in women. Further, it was suggested that these inflexible coordination patterns in women during a competitive game may hinder their ability to properly adjust to the frequent external perturbations common during sports play resulting in injury\(^{48}\). Based on these previous findings, it is possible that dampened lower extremity coordination variability when coupled with fatigue during a game, could potentially lead to an even greater likelihood of injury.

**Purpose**

The purpose of this study was to investigate collegiate level female soccer and field hockey players and the effect of fatigue on lower extremity mechanics during unanticipated sidecutting maneuver. Female athletes have a much greater incidence of injury, particularly non-contact ACL injury, in comparison to males. Since the greatest risk of injury is during the final phase of a game or practice, it is important to observe the
mechanical changes that occur as a result of fatigue. Since the majority of the dynamic
tasks occurring in a game are not pre-planned, this study sought to look at unanticipated
tasks to simulate practice and game conditions. The secondary purpose of this research
was to look at the impact limb dominance under these conditions.

**Significance**

Though there are many studies that look at the effect of fatigue on lower
eextremity mechanics during dynamic sports tasks, there is a lack of research regarding the
effect of unanticipated actions coupled with fatigue. Further, there is a lack of research
looking at differences between the non-dominant and dominant limbs across all three
e lower extremity joints under such conditions. Due to the nature of sports, it is more
realistic to consider that most athletes will not be able to pre-plan these dynamic tasks
during a game. Thus, it is important to increase the ecological validity and practical
implications of the research in this way. Since it is during these unanticipated tasks
towards the end of a game that most non-contact injuries occur, it is important to
investigate how fatigue impacts mechanics in these instances. Previous studies utilizing
anticipated tasks did not observe significant differences in movement mechanics between
pre and post fatigue conditions. More recent research looking at unanticipated tasks and
mechanical differences impacted by fatigue have only evaluated one or two of the joints
in the lower extremity, and only on the dominant limb. Furthermore, there is a lack of
research looking at the kinetic and kinematic changes that occur across the ankle, knee,
and hip during unanticipated and/or fatigue conditions with respect to limb dominance.
By comparing the lower extremity kinetics of a sidecutting maneuver both pre- and post-
fatigue and between the dominant and non-dominant limbs, it may be possible to isolate
specific changes that may place individuals at a greater risk of injury. The purpose of this study was to investigate the effect of fatigue during the unanticipated sidecutting maneuver on lower extremity mechanics. Findings of this study may provide valuable insight for coaches and clinicians working with athletes at high risk of ACL injury.

**Hypothesis**

We hypothesized that fatigue would alter hip, knee, and ankle joint kinetics and kinematics such that: the knee would experience greater external loads (e.g., valgus, varus, internal rotation, and external rotation loads), greater valgus knee torque and more shallow knee flexion angles; the hip would have decreased flexion and abduction, and larger internal rotation; and the ankle would exhibit greater inversion.

**Limitations**

The limitations of this study included: the sample population; the sample was non-random and very specific which can affect its external validity; and effort by the participants during the fatigue protocol could not be fully controlled.

**Delimitations**

The delimitations of this study included using only college aged, female field hockey and soccer players; the study was conducted in a laboratory setting; and the fatigue protocol used was the Yo-Yo Intermittent recovery test to simulate a soccer and/or field hockey match.

**Assumptions**

The researchers assumed that the participants honestly answered the pre-participation health assessment questionnaire; participants used full effort during the
fatigue protocol; and the reliability and validity of the instruments and that they were used properly.

**Operational Definitions**

- Dominant Limb-the patient’s preferred kicking leg

- Non-Dominant Limb-the stance leg opposite the patient’s preferred kicking leg
Chapter 2: Review of the Literature

Introduction
The purpose of this research was to look at female soccer and field hockey players and the effect of fatigue on lower extremity mechanics during unanticipated sidecutting maneuver. Female athletes have a much greater incidence of injury, particularly non-contact ACL injury, in comparison to males. Since the greatest risk of injury is during the final phase of a game or practice, it is important to observe the mechanical changes that occurs pre and post-fatigue. Since the majority of these dynamic tasks are not pre-planned, this study seeks to look at unanticipated tasks to simulate practice and game conditions.

Cutting Maneuver
The cutting maneuver is a dynamic sports task that allows the athlete to change direction from standing, walking, or running. Running combined with the cutting maneuver is the most dangerous of the three as it places the ligaments of the knee at the greatest risk of injury. Depending on the sport, the maneuver varies in terms of the degrees of the cut and its actual performance. The two primary cutting techniques are the sidestep cut and the crossover cut. The sidestep cut is performed by planting with the foot opposite to the intended change in direction while the crossover cut is accomplished by planting with the foot on the same side as the intended change in direction. Though the outcome is the same for both techniques, their execution during the plant and cut
phase and the imposed stresses vary. Both techniques are composed of three separate phases: deceleration, plant and cut, and takeoff \textsuperscript{1}.

**Deceleration**

The deceleration phase may occur over several running gait cycles beginning with the foot to be planted for the cut. The primary goal during deceleration is to decrease the athlete’s momentum by using the greatest amount of force possible in the shortest amount of time so they can begin to move in the new direction \textsuperscript{2}. Ultimately, rapid deceleration of this nature takes place over a few shortened gait cycles, leading to larger braking forces and increased ground contact to attenuate the large eccentric forces with little stress to the joints in the lower extremity as possible \textsuperscript{2}. As the athlete enters the second phase, known as the recovery phase in running gait, the descending foot experiences no backward motion prior to foot strike and the knee is extended. At foot strike the foot quickly plantar flexes so full contact is made with the ground and the lower extremity is ahead of the athlete’s center of mass, opposing the body’s forward momentum \textsuperscript{2}. Upon ground impact, the hip and knee flex and ankle dorsiflexion occurs so as to disperse the impact forces over as many joints as possible which decreases the size of the stress and allows the muscles to do increased negative work \textsuperscript{2}. Since force can only be produced by the body while the foot is in contact with the support surface, the swing leg experiences less time in noncontact to facilitate the need for greater contact or stance phase \textsuperscript{2}. As the body is traveling forward, a deceleration force is created and the torso becomes more upright and the foot dorsiflexes so the tibia angles anterior to the vertical axis and the deceleration force reaches its maximum. This deceleration power is generated primarily by the quadriceps and gastrocnemius \textsuperscript{49}. The body’s pre-activation of these muscles prior to ground contact add to the body’s ability to absorb the extensive eccentric forces during
ground contact. During this portion of the cycle, the body’s kinetic energy decreases as the negative velocity reaches zero prior to the propulsive phase. The body’s kinetic energy is shifted to elastic energy which is then used for the following movement (e.g., the change in direction) \(^2\). Decreased ankle dorsiflexion requires increased knee flexion in order to keep the body’s center of mass behind the stance foot. The anterior position of the foot relative to the center of mass leads to greater horizontal braking ground reaction force. This force is dissipated by ankle dorsiflexion and knee and hip flexion which alleviate the amount of stress applied to the body. The result is a slowing of the forward momentum of the body which will ultimately lead to complete termination of momentum in that direction \(^2\). As the center of mass travels ahead of the foot, the planted foot acts only to support the body’s weight. The second step in the deceleration phase has no change in velocity and is considered passive \(^1\).

During the cutting maneuver, deceleration creates anteroposterior forces on the knee joint. These forces are generated while the foot is planted and the ankle is dorsiflexed just beyond its neutral position. As deceleration is occurring, force is posteriorly applied to the femur so as to inhibit anterior subluxation at the knee joint. The force originates from the extensor mechanism which creates force through the patellofemoral joint with some assistance from the gastrocnemius and the deceleration force is applied through the attached ligaments. The posterior cruciate ligament (PCL), capsular ligaments, and the collateral ligaments tighten in response to anterior translation of the femur relative to the tibia \(^1\). An in-vivo ACL strain case study found that strain on the ACL increased during the flight phase while the knee is extended and pre-activation of the quadriceps and gastrocnemius occurs. Though the strain that occurred during the
flight phase was not significant, the strain continued to increase during the landing phase prior to reaching its peak at the same time as the peak ground reaction force took place, and continued to remain fairly high during the stance phase \(^3\).

**Plant and Cut**

The athlete achieves change in the direction of their momentum during the plant and cut phase. The plant foot controls the ultimate deceleration in the initial direction while the hips cause the torso to rotate in the direction the athlete plans to travel. The athlete then swings the free leg in that direction which generates some acceleration. The plant leg then provides the chief acceleration force in that direction \(^1\).

During this phase, high levels of stress are applied to the capsular ligaments. Due to mechanical differences, stress is medially placed during the sidestep cut, and laterally placed during the crossover cut \(^1\). In order to understand the effect of these forces, it is best to create a distinction between the two cutting techniques.

**sidestep cut.**

In the sidestep cut, the player begins with the body in an upright posture, the hips in flexion, and the knee of the plant leg, or the stance leg, in full extension. The first step during this phase replicates that of the deceleration phase. The athlete maintains their center of mass posterior to the plant foot, which terminates their travel along the initial path. As this deceleration occurs, the torso and pelvis are internally rotated with respect to the femur causing the body’s direction to change and allowing acceleration of the free leg in that new direction. As this occurs, the femur is flexed and externally rotated, the knee is flexed approximately 60 degrees, and the ankle is dorsiflexed. The athlete then pushes off with the stance leg causing its acceleration in the new direction while the knee
and hip extend and the ankle reaches full plantar flexion\(^1\). Once the hips and torso have completely rotated in the new direction, the free leg swings in that same direction which causes acceleration along that path as well as rotational deceleration\(^1\).

When the pelvis is internally rotated, it creates an external rotational torque on the femur that augments the deceleration forces on the medial side of the knee and decreases forces on the lateral side of the knee. These additional stresses act on the medial ligaments of the stance leg. For an athlete with anteromedial rotational instability, this creates a greater risk of injury when performing this technique with the unstable knee for the stance leg\(^1\).

**Kinetics & kinematics.**
Research conducted by Besier, Lloyd, Cochane, and Ackland indicated an elevated risk for knee injury during the cutting maneuver when flexion, valgus/varus, and internal and external rotation loads acted on the knee. The researchers ascertained that external flexion loads when accompanied by greater valgus and internal rotation moments have the strongest influence on the magnitude of stress applied to the ACL, namely when the weight is transferred to the stance leg and the knee is near full extension\(^7,8\). In a study looking at the correlation between lower extremity posture during initial contact and peak knee valgus moment, the researchers noted that there were larger peak valgus moments in conjunction with larger initial contact hip flexion, internal rotation, and knee valgus angles\(^5\).

**Crossover cut.**
In the crossover cut, the pelvis is rotated externally relative to the stance leg. This is accomplished by rotating the pelvis and torso via the internal femoral rotators. Unlike
sidestep cutting, pelvic rotation can also be performed by adducting and internally rotating the free leg. The first part of this phase is also identical to the deceleration phase as the stance leg decelerates the athlete with the ankle dorsiflexed, the hip and knee in flexion, and the tibia angled anterior to the vertical axis. As this deceleration occurs, the pelvis is externally rotated relative to the femur of the stance leg with the hip and knee in flexion and the ankle in dorsiflexion. Once full rotation has been achieved, the free leg begins its forward swing following normal running gait, which accelerates the body in the new direction. Following this, the athlete then accelerates along the new path by pushing off with the stance leg via full extension of the hip and knee and plantar flexion of the ankle. This positions the athlete’s center of mass anterior to their center of pressure.

The stresses imposed on the knee during the crossover cut are like those generated in the sidestep cut, but on the lateral side of the knee. The lateral ligaments take on the additional forces while forces decrease on the medial side of the knee. Likewise, an athlete with anterolateral rotational instability would experience difficulty performing this technique using the unstable knee for the stance leg.

Takeoff

The takeoff phase is quite similar to normal running gait. It includes a support phase and a running phase. The support phase is divided into three events including foot strike, midsupport, and takeoff while the recovery phase includes follow through, forward swing, and foot descent. The key difference between this phase and normal running gait is that the athlete must have a greater forward lean so as to enhance acceleration in the new path of travel.
Anticipated vs. Unanticipated Tasks

More recently, researchers have begun to consider the generalization of their findings based on the ecological validity of their study designs\textsuperscript{14, 50}. Several authors have sought to refine the ecological validity of their work by using unanticipated tasks to minimize the learning effect, and gauge the kinematic and kinetic alterations made by the subjects when presented with a real time situation\textsuperscript{13, 14}. The use of unanticipated dynamic tasks such as the cutting maneuver is meant to mimic the nature of the tasks performance in game situations\textsuperscript{15, 16}.

Previous research in the area of motor control and the response by the central nervous system (CNS) to anticipated and unanticipated actions indicate that a feed-forward mechanism is used in reaction to anticipated actions or stimuli and that the CNS utilizes a preprogrammed plan for anticipated postural modifications\textsuperscript{8, 15, 18}. A feed-forward mechanism can be regarded as learned anticipatory responses to known cues. Essentially, anticipation of a movement can lead to altered reflex responses and postural modifications in order to decrease the impending perturbation and uphold the necessary posture\textsuperscript{17}. In a study by Ilmane and LaRue, the researchers discovered that temporal constraints (self-initiated, anticipation-coincidence, and reaction condition) have a significant effect on anticipatory postural adjustments which are centrally produced as a feed-forward mechanism to offset the mechanical effects of predicted perturbations on stability in dynamic sports tasks. It was noted that the reaction condition required the longest time for the individual to make the anticipatory postural adjustments when compared to the other two conditions\textsuperscript{19}. Research observing joint coordination has indicated that coordination variability provides flexibility in adjusting to perturbations
and is central to the alterations in coordination patterns that occur during movement\textsuperscript{20,21}. Decreased coordination variability has been present in individuals with knee pain as opposed to those without\textsuperscript{20}. Thus, if an individual displays decreased coordination pattern variability during an unanticipated task, it is possible that their ability to adjust to the environmental perturbations commonly experienced during a soccer game or practice may be restricted making them more susceptible to potential injury.

In a study by Besier, Lloyd, Ackland, & Cochrane looking at the anticipatory effects on knee joint loading during running and cutting maneuvers, the authors found that knee joint moments increased during unanticipated conditions when juxtaposed to preplanned maneuvers\textsuperscript{7}. The researchers established that unanticipated maneuvers modified the external moments acting on the knee as a result of the decreased time allotted to generate the proper postural adjustment tactics. It was as a result of these insufficient postural alterations that potentially led to the decreased performance measures of the unanticipated cutting tasks (i.e., decreased cutting angle, decreased speed) and enhanced external loads applied to the knee joint (i.e., valgus, varus, internal rotation, and external rotation loads) in comparison to preplanned tasks. In an effort to more aptly imitate an ecological environment, Besier et al., employed an unanticipated cutting maneuver which resulted in knee moments up to twice the magnitude as compared to those under preplanned conditions like those done by Maliznzak et al., and McLean et al.\textsuperscript{7,51,52} However, this study was limited to a male population\textsuperscript{8}. Research looking at the differences between unanticipated and anticipated lower extremity biomechanics during a sidestep cutting task determined that the unanticipated condition displayed larger knee abduction angles, knee internal rotation, and hip abduction and
decreased knee flexion angles \(^{16}\). The investigators theorized that there may be a greater demand placed on the neuromechanical system when decision making is required.

**Fatigue**

In general, fatigue is considered to be the inability for an individual to maintain a desired level of intensity during a task. Muscle fatigue is described as the loss of maximum force-generating capacity, which may occur for a variety of reasons. Fatigue is variable between individuals as well as the muscle groups and their subsequent fiber types. Depending on the task, muscular fatigue is attributed to central (the brain, brain stem and spinal cord) and/or peripheral (the actual muscles) mechanisms \(^{28}\). It is known that a large portion of this muscular fatigue results from processes occurring internally in the muscle such as interruptions in the excitation-contraction coupling, accumulation of metabolites, and depletion of muscle glycogen \(^{53}\). When the task results in an individual’s inability to completely activate a muscle voluntarily, the mechanism is considered to be central fatigue, which involves events occurring in the brain and spinal cord \(^{54}\). Peripheral fatigue refers to a reduction in a muscle’s force production, due to events occurring within the motor unit \(^{54}\). Both central and peripheral fatigue is generated during intermittent maximal muscle actions \(^{29}\). During intermittent submaximal muscle actions with an ample recovery time between each action, the resulting fatigue has been identified as resulting from peripheral mechanisms \(^{31}\). The effect of fatigue on reflexes and coordination impairs an individual’s performance. If the reflex arc is repeatedly stimulated, it reaches a point where it fails to elicit any type of expected reflex response. It has been noted that the greater the number of interneurons and synapses involved, the more quickly this reflex arc is fatigued. Coordination is
effected in the same way and irradiation of motor impulses to neighboring motor nerve centers leads to a loss in coordination. The relationship between the intensity of the work and endurance may be a fundamental component of performance\textsuperscript{31}.

Both central and peripheral fatigue inhibits an individual’s performance. Central fatigue, or neuromuscular fatigue, can cause an individual to feel tired or exhausted and lead to their capacity to perform an activity or task to be reduced. Peripheral fatigue inhibits their performance by reducing an individual’s ability to produce force despite adequate motivation to execute the desired task.

**Central fatigue**

Central fatigue occurs during lower-intensity, longer duration activities. Several mechanisms have been proposed to cause central fatigue. Suboptimal facilitation from the motor cortex, desensitization of the motoneurons, greater inhibition from group III and IV afferents (which measure the velocity of stretch of a muscle fiber), and reduced facilitation from muscle spindles have all been suggested\textsuperscript{29, 55-57}. Decreased excitation of the Ia afferent neurons resulting from a reduction in the firing frequency of muscle spindles is one such mechanism\textsuperscript{57}. Another possible consideration is a decrease in the size of the excitatory postsynaptic potential generated by each Ia afferent action potential during fatigue, as measured by the Hoffmann reflex (H reflex)\textsuperscript{58}. A reduction in motoneuron excitability, increased presynaptic inhibition of Ia afferents, or both, have been correlated to a decreased H reflex\textsuperscript{58}.

Central fatigue has a large impact on motor control. If it arises from the cerebral cortex, an impaired descending drive or reduced motivation is seen. Development of central fatigue at the level of the spinal cord results in impaired alpha motor neuron firing.
or suboptimal rate of recruitment to generate appropriate muscle force\textsuperscript{25-27}. Central fatigue from impaired alpha motor neuron firing can lead to either loss of recruitment or synergistic activation of multiple muscles\textsuperscript{27}. For repetitive tasks such as gait, the rate slows and the time it takes to complete the task increases with fatigue\textsuperscript{28}.

**Peripheral fatigue**

During higher-intensity, short duration activities, fatigue will primarily occur peripherally. Peripheral fatigue is correlated to the capability of a muscle to perform physical work. As this fatigue occurs, there is impairment to the normal functionality of the nerves and the muscles that are contracting, which translates to a decline in the muscle’s ability to generate force due to the incapability of the body to meet the increased energy demand in the contracting muscles. The most often suggested mechanisms of peripheral fatigue consist of muscle fiber type and its distribution, the readily available energy supply, the length of the muscle, and the muscle’s strength prior to fatigue\textsuperscript{22-24}.

While both central and peripheral fatigue take place during sustained muscle activity in which there is maximal exertion, during sub-maximal exertion, more peripheral fatigue is occurring then central fatigue\textsuperscript{29-31}. In the case of a soccer game, it is presumable that while both central and peripheral fatigue will occur for an individual during a game, peripheral fatigue will be a greater factor due to the inherent quick bursts of activity followed by periods of recovery.

**Fatigue and sports**

The majority of reported ACL injuries that occur in team sports are said to occur towards the end of the game, indicating that fatigue may enhance non-contact ACL injury
Fatigue can influence the muscular mechanisms of the lower extremities, resulting in kinematic changes when comparing fatigue to non-fatigue conditions. Mechanics can be largely impacted by fatigue due to its effect on neuromuscular function. Decreased neuromuscular function can result in decreased shifts in mechanical energy between eccentric and concentric muscle contractions and delayed muscle reaction. Fatigue has also been regarded as a primary component affecting the musculoskeletal system as a result of its connection to diminished proprioception and greater joint laxity and the subsequent reduction in the skeletal muscle’s ability to generate force.

Previous studies looking at the effect of fatigue on various sports tasks have utilized different protocols to simulate game fatigue. This has led to inconsistent findings regarding joint dynamics during these tasks. The variation in fatigue protocols likely contributes to the incongruous mechanical observations of the knee joint.

In a study looking at the effects of fatigue on side-cutting, neuromuscular activity of the hamstrings decreased significantly post-fatigue. The observed decrease in hamstring electromyography (EMG) amplitude represented a modified motor pattern and/or diminished motor unit synchronization. Modification of a motor pattern can impact optimal knee joint stability while diminished motor unit synchronization is a strategy that utilizes muscle antagonist inhibition in order to offset agonist fatigue. Sanna & O’Connor postulated that transverse plane kinetics affected by fatigue could signal possible changes in lower extremity control strategies in order to be able to complete the cutting task. The observed increased knee range of motion in the transverse
plane could indicate that injuries during a game may be occurring as a result of these fatigue related kinetic changes\textsuperscript{36}.

The two main types of fatigue protocols used to study the effect of fatigue on neuromuscular control strategies are short-term and long-term\textsuperscript{36,37}. Short-term protocols used to stimulate fatigue include a series of explosive tasks including vertical jumps and sprints, squats and jumps, and single leg squats, whereas long-term protocols have utilized 60 minute shuttle runs. In a study by Lucci et al. (2011), both short-term and long-term fatigue protocols elicited altered hip and knee kinetic and kinematics during sidestep cutting in female soccer players, and, after only five minutes of performing either protocol, mechanical changes in the lower extremity took place that could enhance the athletes risk for injury.

In an evaluation of the effect of fatigue on single limb landing, the results indicated that there was not an overall effect of fatigue on valgus knee angles during anticipated landing tasks. However, when the direction of the landing task was unanticipated, there was a significant increase in knee valgus angles. This may have occurred due to the effect of fatigue on coordination and timing. These results suggest that there might be an increased risk for ACL injury when both fatigue and decision-making conditions are present\textsuperscript{64}.

Sports such as soccer and field hockey involve intermittent exercise with high intensity activities such as jumping, turning, cutting, running and sprinting\textsuperscript{65,67}. Research looking at the physiological components such as heart rate and metabolic measures from blood and muscle samples obtained during competition have found that
athletes in these sports experience high aerobic work and anaerobic work during competition. Initially, the capacity of these athletes was evaluated based on continuous exercise tests (e.g. the Leger shuttle-run test, VO_{2max} test). Development of the Yo-Yo Intermittent recovery (IR) tests were in response to the lack of relevance of continuous exercise tests for athletes participating in intermittent sports. The Yo-Yo IR tests are comprised of 2x20m shuttle runs with increasing speeds, followed by a 10 second recovery period and the participant continues until they can no longer maintain the speed and cover the distance in the allotted time. The Level 1 (Yo-Yo IR1) test begins at a slower speed and has more modest increases in speed then the level 2 (Yo-Yo IR2) test. For a less trained individual, the Yo-Yo IR1 test assesses the athlete’s ability to complete a repetitive intense exercise bout with a large contribution of anaerobic work.

Several studies have observed the possible relationship between performance during competition and performance of the Yo-Yo Intermittent Recovery tests. Specific to soccer, there was a significant correlation between Yo-Yo Intermittent Recovery 1 performance and the total amount of high intensity exercise for professional players during a match. Research by Krstrup et al., found that amount of high intensity running completed at the end of each match half was significantly correlated to the Yo-Yo IR1 performance by elite female soccer players. The reliability and validity are well supported and strong correlations have been made between the performance of the Yo-Yo test and the amount of high intensity running during a soccer match, unlike other testing methods such as repeated sprint tests, the Leger multistage fitness test, and VO_{2max} testing. Krstrup et al, determined that performance of the Yo-Yo IR1 test was the same when they repeated the test within a week. Research by Thomas et al.
assessed the test-retest reliability with 16 recreationally active subjects and attained a correlation coefficient of 0.95 (p< 0.01) and the coefficient of variation being 8.7% \(^73\).

**General Anatomy of the Knee**

The knee is a hinge joint formed by the femur and tibia. The patella is a sesamoid bone that protects the anterior side of the joint. The patellar tendon originates from the inferior portion of the patella and inserts on the tibial tubercle. The quadriceps muscle group causes knee joint extension and is made up of the rectus femoris, the vastus medialis, the vastus lateralis, and the vastus intermedius. This muscle group serves as an antagonist to the anterior cruciate ligament (ACL) and can decrease posterior subluxation if a posterior cruciate ligament (PCL) injury occurs. The hamstring muscle group, made up of the biceps femoris, semimembranosus, and semitendinosus, acts as antagonists medially and laterally to the PCL decreasing anterior subluxation.

Articular cartilage pads the joint, covering the ends of the femur and tibia and also the posterior side of the patella. The medial and lateral menisci are cartilage pads that function in load bearing, controlling rotation, and stabilizing translation. The collateral ligaments are located on the lateral and medial sides of the joint stabilizing the knee by limiting frontal plane motion. The posterior cruciate ligament prevents excessive posterior translation of the tibia. The ACL originates on the posterior side of the intercondylar notch and inserts on the anterior side of the intercondylar eminence. The ACL acts in preventing hyperextension and anterior translation and it guides tibial rotation as the knee extends \(^74\).
General Ankle Anatomy

The ankle is comprised of three joints including the talocrural joint, the subtalar joint and the inferior tibiofibular joint. Subtalar and talocrural joint motions include inversion/eversion, dorsiflexion/plantarflexion, and abduction/adduction, or pronation (dorsiflexion, abduction, and eversion) and supination (plantarflexion, adduction, and inversion). The primary bones that make up the ankle include the distal tibia, fibula, and talus. The tibia is the bone that bears the greatest amount of weight in the leg. The distal articular surface of the tibia forms the top of the ankle mortise, and the medial malleolus forms the medial border of the mortise and is the attachment site for the deltoid ligaments. The fibula is a long, thin bone lateral to the tibia and is a site for both ligamentous and muscular origin and attachment and creates lateral stability for the ankle mortise. The lateral malleolus is an attachment site for the lateral ligaments of the ankle and limits eversion, while the medial malleolus limits inversion. The lateral side of the ankle is a more prevalent site for sprains which can lead to ligamentous avulsion from the lateral malleolus when the ankle is inverted. The talus articulates with the distal tibia and its medial and lateral borders articulate with the medial and lateral malleoli.

The talocrural joint is a modified synovial hinge joint formed by the articulation between the talus, tibia, and fibula. It is surrounded by a joint capsule. If any of the ligaments of the ankle are torn, it generally results in harm to the joint capsule as well as irritation of the synovial lining. The only ligament that is an exception is the calcaneofibular ligament, which exists extracapsularly. The three ligaments that exist on the lateral portion of the ankle providing support to the talocrural joint are the anterior talofibular ligament, the calcaneofibular ligament, and the posterior talofibular ligament.
The four medial ankle ligaments form the deltoid ligament that supports the medial aspect of the ankle. The four ligaments are: the anterior tibiotalar ligament, the tibiocalcaneal ligament, the posterior tibiotalar ligament, and the tibionavicular ligament.

The syndesmosis joint is comprised of the convex facet on the fibula which is buffered from the concave tibial facet by dense fatty tissue. The inferior anterior and posterior tibiofibular ligaments, and the crural interosseous ligament maintain the syndesmosis. The interosseous membrane is a strong fibrous tissue that fixes the fibula to the tibia and is a point of origin for many muscles acting on the ankle and foot. On the proximal side, an opening creates a passage way for the deep peroneal nerve and anterior tibial artery. The distal side blends into the anterior and posterior tibiofibular ligaments creating support for the distal tibiofibular syndesmosis joint.

The anterior compartment dorsiflexor muscles include the tibialis anterior, the extensor hallucis longus, the extensor digitorum longus, and the peroneus tertius. The tibialis anterior is the prime ankle dorsiflexor and supinator. The extensor hallucis longus aides in supination while the extensor digitorum longus assists with pronation. The peroneus tertius is parallel to the fifth tendon of the extensor hallucis longus and it aides in pronation. Across the anterior portion of the ankle mortise is the extensor retinaculum which functions in securing the distal tendons of the muscles of the anterior compartment as they cross the talocrural joint.

The lateral compartment structures include the peroneus longus and the peroneus brevis. These muscles contribute mainly to eversion and also to plantarflexion. The
peroneal tendons are held in position posteriorly by the superior and inferior peroneal retinaculum.

The posterior compartment structures are divided superficially and deeply. The superficial posterior structures include: the triceps surae muscle group, made up of the gastrocnemius and soleus, and the plantaris. The gastrocnemius and plantaris originate on the posterior aspect of the femoral condyles while the soleus originates off the posterior tibia. All three muscles insert on the calcaneus via the Achilles tendon. The gastrocnemius and soleus are the primary movers during plantarflexion. The deep posterior compartment structures include the flexor digitorum longus and the flexor hallucis longus which flex the toes and assist in plantarflexion and inversion of the ankle. The subtendinous calcaneal bursa is between the Achilles tendon and the calcaneus and acts to decrease friction between these two structures. Located between the posterior aspect of the Achilles tendon and the skin is the subcutaneous calcaneal bursa which protects the tendon from trauma and decreases friction.

**General Hip Anatomy**

The acetabulofemoral joint is a joint formed by the femur and acetabulum on the lateral aspect of the pelvis. The superior wall of the acetabulum is made by the ilium, while the inferior wall is created by the ischium, and the medial wall by the pubis. Centered within the fossa is a depression for the ligamentum teres. The outer rim of the acetabulum is lined by a thick ring of fibrocartilage called the labrum. The femoral head is round with its articular surface covered thickly by hyaline cartilage except for a central depression where the ligamentum teres attaches. The head of the femur is connected by
the femoral neck and shaft, and the head is angled at approximately 125 degrees in the frontal plane. This is referred to as the angle of inclination.

The iliofemoral ligament originates from the anterior inferior iliac spine and splits inserting on the distal aspect of the anterior intertrochanteric line and on the proximal aspect of the anterior intertrochanteric line and the femoral neck. This ligament reinforces the anterior portion of the joint capsule, limiting extension, adduction, and abduction and allowing individuals to stand upright with minimal use of muscles. The pubofemoral ligament originates from the pubic ramus and inserts on the anterior aspect of the intertrochanteric fossa, limiting abduction and hyperextension of the hip. The ligamentum teres serves as a pass way for the artery of the ligamentum teres and does little in terms of hip stabilization but provides the primary blood supply to the head of the femur. The inguinal ligament originates on the anterior superior iliac spine and inserts on the pubic symphysis. This ligament holds the soft tissues as they move anteriorly from the trunk to the lower extremity.

Hip joint motion is controlled by groups of large extrinsic and small intrinsic muscles. The larger muscle groups flex, extend, and internally rotate the joint. The smaller intrinsic muscles externally rotate the hip. During cutting and running, the abductors and adductors stabilize the hip. The anterior muscles include the rectus femoris, the sartorius, and the iliopsoas group (psoas major, psoas minor, and iliacus). The medial musculature includes the adductor longus, adductor magnus, adductor brevis, the pectineus, and the gracilis. The lateral muscles include the gluteus medius, the tensor fasciae latae, the piriformis, quadratus femoris, obturator internus, obturator externus,
gemellus superior, and gemellus inferior. The posterior muscles include the gluteus maximus and the hamstring muscle group.

There are four main bursae located in the hip and pelvic region that function to reduce friction between the gluteus maximus and adjacent bony structures. These bursae include: the trochanteric bursa; the gluteofemoral bursa; the ischial bursa; and the iliopsoas bursa.

Gender
In comparison to males, female athletes are four to six times more prone to ACL injury. Due to the increased participation of females in sports, it is important to examine the potential factors that contribute to the increased risk of injury. Previous research has identified potential anatomical, hormonal, and neuromuscular differences that may be attributed to the disparity in injury rates between males and females with regards to the knee.

When performing the sidestep cutting maneuver, women have been found to have decreased hip flexion and abduction, and larger internal rotation when compared to men. Further, they have demonstrated less knee flexion and greater knee internal rotation, larger knee abduction and pronation of the posterior foot. Research by McLean, Huang, and van den Bogert found several gender differences when looking at lower extremity posture at contact and peak knee valgus moment during sidestep cutting. The researchers discovered that women displayed greater normalized peak valgus moments in the stance phase of sidecutting and peak valgus moment is more responsive to initial contact hip internal rotation and knee valgus excursions in women, which may indicate a greater potential for injury.
Sigward and Powers found gender differences during side-step cutting. The researchers identified women as having smaller sagittal plane moments and larger frontal plane moments during the early deceleration phase. During early deceleration, the women displayed a valgus moment during while the men had a varus moment. Overall, the women displayed peak frontal moments relative to body mass that were two times larger than the male subjects. The authors noted that female subjects had a valgus torque at the knee while the male subjects had a varus torque on the knee. These findings are consistent with those determined by McLean, Huang, and van den Bogert. Previous studies utilizing both modeling and in vitro techniques have established that valgus torque on the knee enhances the load placed on the ACL, especially at shallow knee flexion angles such as those during the early deceleration phase, placing women at greater risk for injury.

Pollard, Heirdescheit, van Emmerik, and Hamill, found that women displayed less coordination variability during an unanticipated sidecutting task. As alluded to by Hamill et al., and reduction in variability in intralimb couplings is potentially related to more rigid coordination patterns, which could lead to increased risk of lower extremity injury. The authors determined that the gender differences in lower extremity coordination variability predominantly observed in the initial loading phase of an unanticipated cutting maneuver might attribute to the greater incidence of noncontact ACL injuries in women. Further, it was suggested that these inflexible coordination patterns in women during a competitive game may hinder their ability to properly adjust to the frequent external perturbations common during sports play resulting in injury. Based on these previous findings, it is possible that dampened lower extremity
coordination variability when coupled with fatigue during a game, could potentially lead to an even greater likelihood of injury.

**Anatomical Differences**

There are several different hypotheses regarding sex related anatomical differences that would potentially contribute to increased knee injury rates in females. The first theory is centered around the difference in Q-angle between sexes. The Q-angle is the angle formed by the femur from the hip joint to the knee joint. Despite increased Q-angle in females, no association was found between a larger Q-angle and ACL injury \(^ {74}\). The second theory indicates that the smaller femoral notch width relative to the size of the ACL predisposes women to ACL injury. Despite this assertion, research regarding this is contradictory \(^ {74}\). The final theory suggests that a narrow intercondylar notch leads to a small ACL, increasing the risk of the knee to ACL injury, though research surrounding this notion is contradictory as well \(^ {75}\).

**Hormonal Differences**

Sex steroid hormones and the menstrual cycle have been considered as risk factors for the disproportionately greater incidence of non-contact ACL injuries in female athletes compared to men \(^ {77,78}\). Several studies conducted by Shultz et al., \(^ {79-81}\) have determined that joint laxity in the knee fluctuates across the menstrual cycle and correlates to absolute concentrations of sex steroid hormones. Although there is conflicting research, some investigators have noted that a greater number of non-contact ACL injuries occur around the late follicular phase, or ovulation, when there is a steep increase in the level of estradiol, as opposed to the early follicular and luteal phases of the cycle \(^ {77,78,82}\). Studies have indicated that estrogen binds to receptors on the ACL, increasing its laxity. This increased laxity could possibly account for injury rate
differences between sexes. Males tend to have less laxity in the anterior portion of the knee along with greater knee flexor strength. Estrogen has also been found to have a large effect on muscle function, the strength of the tendons and ligaments, and the central nervous system. A marked decrease in motor skills has been recognized during the week prior to menstruation 75.

**Neuromuscular Differences**

Neuromuscular activation of the hamstrings and quadriceps may facilitate dynamic frontal-plane knee joint stability due to their abduction and/or adduction moment arms 83. Two general types of neuromuscular activation tactics have been suggested to reduce external loading of the knee during dynamic sports tasks 83, 84. The first method utilizes selective activation of muscles that have the mechanical ability to offset the external load, and the second method entails arbitrary co-contraction without discrimination due to mechanical advantage. Previous studies indicate that women may utilize a selective activation method that supports abduction loading, which can be a cause of ACL injury. Women tend to activate the lateral quadriceps and hamstrings while having little activation of the medial thigh muscular. Activation of the medial thigh has been found to resist abduction loads, thus, the method used by women might potentially lead to injury 82, 85-87.

Lower extremity muscle activation differences during side-step cutting have been observed between sexes. In a study by Hanson, Padua, Blackburn, Prentice, and Hirth, the researchers found that female soccer players display a quadriceps dominant muscle activation pattern during both a running-approach side-step cut and box-jump side-step cutting maneuver in comparison to male soccer players, placing them at a greater risk of
injury. Also noted in the study was the greater Gluteus medius activation in female subjects during the first half of the initial stance phase in sidecutting as well as greater vastus lateralis activation during sidecutting then the male subjects. Research has found that contraction of the quadriceps increases loading of the ACL unless the contraction of the hamstrings is large enough to offset the quadriceps muscle contraction.

General Mechanisms of ACL Injury

The two primary classifications for anterior cruciate ligament (ACL) injury mechanisms are contact and noncontact. A noncontact ACL injury refers to those sustained when the player has no physical contact with another player, the ball, or another object other than the ground. Previous studies note that 70 to 84% of all ACL injuries are non-contact in nature\(^\text{11,46}\). The majority of these injuries occur during changes in direction, rapid deceleration while running, cutting maneuvers combined with deceleration, landing after a jump with the knee in or close to full extension, and pivoting on a planted foot with shallow knee flexion\(^\text{90,91}\). The major components involved in the aforementioned conditions include knee valgus, varus, internal rotation, external rotation moments, and force being anteriorly translated\(^\text{92}\).

A study by Zebis, et al., found that one of the most frequently reported non-contact ACL injury mechanisms is the plant-and-cut maneuver which leads to forceful knee joint valgus and either internal or external tibial rotation with a very small knee flexion angle. During these tasks, it appears that multi-planar knee loading (particularly loading in the transverse and frontal planes) causes an exceedingly large quadriceps contraction without the necessary magnitude of hamstring co-contraction\(^\text{11}\).
When looking closer at knee flexion angles, Nagano, Ida, Akai, and Fukubayashi, determined that knee flexion angles less than 30 degrees resulted in a large strain force on the ACL caused by quadriceps contraction, especially during unilateral landing as a means to prevent falling. Loading of the quadriceps can lead to anterior tibial displacement, knee internal rotation, and knee valgus motions.

During rapid deceleration, large quadriceps contractions at small knee flexion angles place individuals at a greater risk of injuring the knee. This has been observed more so in female athletes as they tend to be quadriceps dominant in response to anterior tibial translation, while male athletes tend to recruit the hamstrings to a greater degree than the quadriceps. The hamstrings act to resist strain on the ACL, serving as an agonist to the ACL, whereas the quadriceps act as antagonists, increasing strain on the ACL, particularly when the knee flexion angle is small. It has also been noted that during these non-contact injuries, the knee went into valgus while simultaneously rotating either internally or externally. This was also found to occur in a hyper-extended knee joint position from a shallow knee flexion angle of approximately five to twenty degrees. The risk of the ACL sustaining larger anterior loads is greater near full knee extension when the ACL is acting to prevent anterior translation of the tibia relative to the femur.

Conclusions

Though there are many studies that look at the effect of fatigue on lower extremity mechanics during dynamic sports tasks, there is a lack of research regarding the effect of unanticipated actions coupled with fatigue. Due to the nature of sports, it is more realistic to consider that most athletes will not be able to pre-plan these dynamic tasks during a game. Thus, it is important to increase the ecological validity and practical
implications of the research in this way. Since it is during these unanticipated tasks
towards the end of a game that most non-contact injuries occur, it is important to
investigate how fatigue impacts mechanics in these instances. Previous studies utilizing
anticipated tasks did not observe significant mechanics differences between pre and post
fatigue conditions. Furthermore, there is a lack of research looking at the kinetic and
kinematic changes that occur across the ankle, knee, and hip during unanticipated and/or
fatigue conditions. There is also a lack of research examining differences between limbs
during the sidecutting maneuver. By comparing the lower extremity kinetics of a
sidecutting maneuver both pre and post fatigue, it may be possible to isolate specific
changes that may place individuals at a greater risk of injury. The purpose of this study is
to investigate the effect of fatigue on lower extremity mechanics during the unanticipated
cutting maneuver. The secondary purpose of this research is to examine differences
between limbs with respect to limb dominance.
CHAPTER 3: Manuscript

THE EFFECT OF FATIGUE ON LOWER EXTREMITY MECHANICS DURING THE UNANTICIPATED SIDE CUTTING MANEUVER

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Abstract
Fatigue has been observed to affect lower extremity mechanics during the cutting maneuver. However, there is a lack of research examining the effect of fatigue and limb dominance on lower extremity mechanics during unanticipated sidecutting. Objectives: This research sought to assess mechanical differences pre- and post-fatigue and with respect to limb dominance. Design: Repeated measures. Methods: Thirteen female collegiate soccer and field hockey players performed right and left unanticipated sidecutting following the Yo-Yo Intermittent Recovery test (Yo-Yo IR), a two minute treadmill run at a predicted VO\(_{2\text{max}}\), and maximum vertical jumps. Mechanical measures of ankle, knee, and hip motion were obtained during the stance phase of the cut. Repeated measures 2x2 ANOVAs were performed to look at fatigue and limb differences. Alpha level set \textit{a priori} at 0.05. Results: At initial contact and peak stance, significant changes pre- to post-fatigue were observed. At initial contact there was a reduction in knee flexion angles along with increased ankle dorsiflexion angles post-fatigue. At peak stance: increased knee adductor moments post-fatigue; greater ankle eversion moments on the dominant limb (DL) as well as increased eversion moments post-fatigue for both limbs. There was a differential effect of fatigue on peak hip abduction angles and hip internal rotation angles at initial contact which were altered in the DL only; decreased hip adductor moments occurred post-fatigue as well as decreased power absorption. Conclusions: Results from this study indicate that lower extremity mechanics are altered as an effect of fatigue such that injury risk may be elevated.

Keywords: Biomechanics; Limb Dominance; Anticipation
**Introduction**

The sidecutting maneuver is a dynamic sports task that allows the performer to change direction from standing, walking, or running. Improper mechanical execution of the sidecut can place the ligaments of the knee at the greatest risk of injury. Given that the majority of dynamic cutting tasks are not pre-planned during games, anticipated maneuvers are likely not a true reflection of lower extremity mechanics.

The use of unanticipated dynamic tasks such as a cutting maneuver is meant to mimic the nature of the task’s performance in game situations. Ilmane and LaRue discovered that temporal constraints (self-initiated, anticipation-coincidence, and reaction condition) have a significant effect on anticipatory postural adjustments. These anticipatory postural adjustments are centrally produced as a feed-forward mechanism to offset the mechanical effects of predicted perturbations on stability in dynamic sports tasks. Thus, during an unanticipated task an individual’s ability to adjust to the environmental perturbations commonly experienced during a game or practice may be restricted, making them more susceptible to potential injury. Research looking at the differences between unanticipated and anticipated lower extremity biomechanics during sidecutting determined that the unanticipated condition displayed greater knee abduction and internal rotation, hip abduction, and decreased knee flexion.

The majority of reported ACL injuries in team sports occur towards the end of the game, indicating that fatigue may enhance non-contact ACL injury risk. Fatigue can influence the muscular mechanisms of the lower extremities, resulting in kinematic changes when compared to non-fatigue conditions. Research has demonstrated that changes in transverse plane kinetics could be indicative of injury mechanisms occurring
as a result of these fatigue-related changes.\textsuperscript{36} In an evaluation of fatigue on single limb landing, increases in knee valgus angles were reported when landing direction was unanticipated, and may have been due to the effect of fatigue on coordination and timing. These results suggest that ACL injury risk may increase when both fatigue and decision-making conditions are present.\textsuperscript{64}

When performing the sidecut, women have been found to have kinematic and kinetic differences that increase their risk of injury four-to-six times above their male counterparts.\textsuperscript{46} These differences include: decreased hip flexion and abduction, larger hip internal rotation, less knee flexion, greater knee internal rotation and abduction, pronation of the plant foot, and greater normalized peak valgus moments during the stance phase.\textsuperscript{47} Studies utilizing both modeling and in vitro techniques have established that valgus torque on the knee enhances the load placed on the ACL, especially at shallow knee flexion angles such as those during the early deceleration phase, placing women at greater risk for injury.\textsuperscript{7,9-11} Female athletes have also been observed as having a reduction in their performance of the sidestep cut when it was unanticipated, which could be attributed to less coordination variability during an unanticipated sidecut compared to men. It has been suggested that these inflexible coordination patterns during a competitive game may hinder females ability to properly adjust to the frequent external perturbations common during sports play, resulting in injury.\textsuperscript{48} Based on these previous findings, it is important to study the effect of fatigue on unanticipated sidecutting as dampened lower extremity coordination variability when coupled with fatigue during a game, could further exacerbate injury risk.
Previous research has also assessed lower-limb dominance related to the risk of ACL injury and athletic performance.\textsuperscript{41, 42} Though significance between limbs has not been found, limb asymmetries may still pre-dispose athletes to injury.\textsuperscript{41, 42, 94} Contrasting biomechanical variables between dominant and non-dominant limbs during single leg drop landing, suggest that the dominant limb demonstrated greater thigh strength, greater knee flexion range of motion, and enhanced proprioception in an athletic population. Thus, by identifying kinetic and kinematic differences pre- and post-fatigue between limbs may enhance our knowledge and abilities to design preventative techniques for training, rehabilitation, and conditioning.\textsuperscript{45}

Though several studies have looked at the effect of fatigue on lower extremity mechanics during dynamic sports tasks, few have observed its effects on unanticipated actions and limb dominance. Although previous studies utilizing anticipated tasks have not observed differences due to fatigue, it is more realistic to consider that most athletes will not be able to pre-plan these dynamic tasks during a game. Since unanticipated cutting towards the end of a game are accompanied by increased risk of injury, it is important to investigate how fatigue impacts mechanics in these instances. Furthermore, there is a lack of research assessing kinematic and kinetic changes occurring across the ankle, knee, and hip during unanticipated and/or fatigue conditions. Given that the body functions most efficiently when its joints are aligned, any deviations may result in compensatory mechanisms to re-establish equilibrium. Evaluating all three joints provides a better depiction of lower extremity mechanics and how all three joints are affected by fatigue.
The primary purpose of this study is to investigate the effect of fatigue on lower extremity mechanics during the unanticipated sidecut. The secondary purpose is to evaluate differences between the dominant and non-dominant limbs. We hypothesize that fatigue will alter lower extremity kinetics and kinematics such that: the knee will experience greater external loads and more shallow knee flexion angles; the hip will have decreased flexion and abduction, and larger internal rotation; and the ankle will exhibit greater inversion.
Methods

Thirteen college-aged NCAA Division I female soccer and field hockey players volunteered for this study (mean age = 20.31±1.84years; height = 1.68±5.7m; mass = 61.99±6.45kg). A power analysis was performed to confirm the sample size with 80% statistical power with an alpha level of 0.05. Participants were excluded if they reported any of the following: a history of ACL injury or surgery; history of knee injury that may have resulted in joint laxity (e.g., PCL, MCL, or LCL injury); musculoskeletal injuries in the previous six months that prevented them from participating in activity (practices and games); or any physical or neurological condition that impaired their ability to complete the task required. A health history questionnaire was used to assess health status, and all participants signed a university approved informed consent document.

Three-dimensional kinematic and kinetic data was collected with a passive, 12-camera (F40) Vicon motion-analysis system (VICON, Oxford Metric Ltd., Oxford, UK) sampling at 240 Hz. Spherical retro-reflective markers (14mm and 25mm) were placed on specific anatomical landmarks following a modified Plug-in Gait model. Ground reaction forces were collected using two AMTI force platforms (Model OR6-7-2000, Advanced Mechanical Technologies Inc., Watertown, MA, USA) embedded within the testing floor sampling at 2400 Hz.

Participants came to the Ball State University Biomechanics Laboratory for a single 90 minutes testing session. All individuals were outfitted in compression clothing, standardized indoor soccer footwear, and had anthropometric measures taken. Using a
modified plug-in-gait model, markers were placed on anatomical landmarks of both the upper and lower body that included 4-marker clusters on each thigh and shank. The dominant limb (DL) was defined as the leg used to kick a ball, and the opposite limb was defined as the non-dominant limb (NL) \(^{41}\). All participants identified their DL as the right limb. Participants performed a self-selected dynamic warm up for ten minutes, followed by three vertical jumps to determine maximum jump height. Participants practiced at least three of each cutting task (i.e., cut left, cut right and stop) or until they felt comfortable. Timing gates were set up 3m from the center of the force plates and as participants ran through the timing gates, custom built computer software randomly generated a projection of the dynamic task onto a screen in front of the participants (i.e., direction arrows or a stop sign). Tape lines were placed 45° to the right and left of the plate to guide the angle of the cuts. The pre-fatigue dynamic task trials were then performed, with 45-second rest period between pre-fatigue trials to minimize fatigue. \(^{40}\) The pre-fatigue portion of the testing was terminated once the participant had completed four good right and four left cutting trials, consisting of placement of the stance foot on the force plate and then a 45° cut in the direction contralateral to the stance foot. \(^6\)

After completing the pre-fatigue dynamic task trials, participants performed the YYIRT. \(^{69}\) This protocol consisted of repeated high intensity 20 meter shuttle runs starting at 10 km/h and increasing on successive trials by 0.5 km/h with 10 seconds of recovery after each trial (20m x 2), and was repeated until the athlete was unable to successfully complete two 20m sprints in the allotted time. This test has been proven to be valid and reliable with ~5% variation between tests \(^{72}\) and has been correlated to match play in elite male soccer players. \(^{69}\) The fatigue testing was conducted in a
gymnasium next to the laboratory. To ensure that participants maintained their fatigued state once back in the laboratory, they ran for two minutes on the treadmill in the testing area at their estimated VO$_2$max speed as calculated by the YYIRT. Immediately following the treadmill task, participants performed vertical jumps until unable to reach 80% of their maximum vertical jump height for three successive jumps. Finally, participants performed the post-fatigue randomized dynamic tasks trials, without a rest period between each trial. The post-fatigue trials were considered complete once four good right and left cuts had been performed.

The raw marker trajectory data was reconstructed in Nexus (VICON, Oxford Metric Ltd., Oxford, UK) and further processed in Visual3D (C-Motion, Germantown, MD, USA) with the use of standard segment and joint definitions. Net joint moments were calculated using standard inverse dynamics equations. Raw 3D coordinate data for markers were filtered using a fourth-order Butterworth filter with a cutoff frequency of 8 Hz which is consistent with previous studies. Three-dimensional knee angles were calculated using a joint coordinate system approach. Repeated measures 2x2 (time x leg) ANOVA’s were performed to look at: ankle, knee, and hip angles in all three planes at initial contact; peak ankle, knee and hip angles and moments in the frontal plane, and peak power absorption over the entire stance phase. The alpha level was set at 0.05 and analyses were performed using SPSS version 19.0 (SPSS Inc., Chicago, IL, USA).

**Results**

The descriptive statistics for kinetic and kinematic data are in Tables 1 and 2. On average, the participants completed the YYIRT at level 17 (SD 5.4) at approximately
96% of their predicted maximum heart rate. Dependent t-tests across all cutting trials confirmed there were no significant differences ($p \geq 0.05$) in cutting speed between pre- and post-fatigue and between limbs.

We observed significant changes pre- to post-fatigue when collapsed across limbs. The knee experienced decreased flexion angles at initial contact ($F_{1,11} = 37.25$, $p \leq 0.001$, $\eta^2 = 0.77$), and increased peak adductor moments ($F_{1,13} = 5.58$, $p = 0.034$, $\eta^2 = 0.3$). The ankle displayed increased dorsiflexion angles ($F_{1,11} = 5.08$, $p = 0.046$, $\eta^2 = 0.5$) at initial contact, and increased peak eversion moments ($F_{1,11} = 7.34$, $p = 0.019$, $\eta^2 = 0.38$). The hip displayed decreased flexion angles ($F_{1,11} = 21.06$, $p = 0.001$, $\eta^2 = 0.66$) at initial contact, decreased peak adductor moments ($F_{1,11} = 9.104$, $p = 0.011$, $\eta^2 = 0.431$) and decreased hip power absorption ($F_{1,11} = 5.2$, $p = 0.042$, $\eta^2 = 0.3$).

Significant differences were only observed for the ankle between limbs when collapsed across time. Greater peak ankle eversion moments were noted on the DL ($F_{1,11} = 6.7$, $p = 0.024$, $\eta^2 = 0.36$) and the NL exhibited greater ankle power absorption ($F_{1,11} = 12.15$, $p = 0.004$, $\eta^2 = 0.5$).

There were significant interaction effects for peak hip abduction angles ($F_{1,11} = 6.75$, $p = 0.023$, $\eta^2 = 0.36$) and for hip internal rotation angles for limb and time ($F_{1,11} = 6.36$, $p = 0.028$, $\eta^2 = 0.63$), however no significant simple main effects were found for either limb or time on the two measures.

**Discussion**

The purpose of this study was to investigate the effect of fatigue on lower extremity mechanics during the unanticipated sidecut and to evaluate differences between
limbs. Our main findings determined that participants performed the sidecut with a more vertical lower limb post-fatigue, which is consistent with previous research.\textsuperscript{34,40} These findings are consistent with the current literature indicating fatigue alters mechanics such that the knee is placed in a position associated with an increased injury risk.

With respect to the knee, we observed increased peak adductor moments following fatigue, which have been strongly linked to injury risk.\textsuperscript{6,34,36} These increased adductor moments coupled with anterior tibial force may increase ACL loading.\textsuperscript{9-11} During cutting, knee flexion functions in attenuating the increased loading during the deceleration phase. It also lowers the athlete’s center of gravity, decreasing the moment of inertia of their body about their foot and creating a more stable base of support during the cut.\textsuperscript{52} The increased adductor moments coupled with decreased knee flexion angles compromise the integrity of the knee joint, increasing injury risk due to the resulting large quadriceps forces and insufficient co-contraction of the hamstrings. We also observed increased peak ankle eversion moments which may have been a mechanical strategy by the lower limb in conjunction with the increased peak knee adductor moments as a means of stabilizing the tibia.

Increased dorsiflexion at initial contact may also have been a compensatory mechanism enhancing ankle power absorption through the stretch reflex mechanism, and in response to the decreased ability of the hip to absorb power post-fatigue. The finding of decreased power absorption at the hip may be a result of neuromuscular fatigue. The decreased hip adductor moments may have also been a compensatory mechanism attempting to reduce external loading, thereby allowing fatigued hip adductor muscles to produce less force to control hip motion. Decreased neuromuscular function can result in
decreased shifts in mechanical energy between eccentric and concentric muscle contractions and delayed muscle reaction \(^{62}\), and also as a primary component in diminished proprioception and greater joint laxity \(^{32}\) and ultimately a reduced ability to generate force.\(^{28,33}\) Decreased hip flexion at initial contact produces a more vertical limb. This positions the foot closer to the midline of the body and results in decreased gravitational moment of inertia acting on the body’s center of mass, and decreases the need for large internal moments to be created by the hip musculature.

Anticipation of a movement can lead to altered reflex responses and postural modifications in order to decrease the impending perturbation and uphold the necessary posture.\(^ {17}\) In the current study, the cutting maneuvers were unanticipated both pre- and post-fatigue, which limited the time the participants had to perceive the stimulus and coordinate lower extremity mechanics. It is possible that participants constrained mechanics under both the fatigue and non-fatigue conditions, impacted variables such as hip abduction, and ankle inversion, which were hypothesized to be altered by fatigue.

Though previous studies have not identified a significant relationship between lower limb dominance and potential for injury, differences in mechanics between limbs may indicate increased risk of injury.\(^ {42}\) This study observed significant differences in frontal plane peak ankle moments and powers. The significant interaction effects for hip internal rotation angles at initial contact indicate that the DL was more influenced by fatigue. The effect was also evidenced with decreased peak hip abduction and internal rotation angles following fatigue that resulted in the DL more closely mimicking mechanics seen in the NL. Though both limbs were affected by fatigue, possible differences in motor control strategies may have impacted the DL’s ability to control hip
motion, leading to compensatory mechanisms to decrease external loading as a means to prevent injury following fatigue. Though the DL was differentially affected by fatigue, it appears that the NL is at a greater risk of injury given its mechanics both pre- and post-fatigue, including decreased hip abduction and internal rotation angles. Previous research has identified an increased trend towards injury to the left limb in female athletes which is consistent with our findings as all 13 participants identified their left limb as the NL.²

The findings from this study provide new information pertaining to ACL injury mechanisms in elite level female athletes. Although the findings help to improve our understanding on this injury there are some limitations. The Yo-Yo Intermittent Recovery Test (YYIRT) has been observed to produce similar physiological effects experienced during a soccer match and thus may better simulate fatigue experienced during match play.⁶⁹ However, it may vary in its influence on the cutting maneuver due to the significantly decreased performance time relative to actual game play. With the addition of maximum vertical jump height and the 2-min treadmill run, we induced fatigue using several methods in an attempt to ensure that the athlete maintained a fatigued state during testing. Future research should include other sports, competitive levels, age groups, and males to identify whether similar trends apply across different groups.

**Conclusion**

Prior research has determined that following fatigue, mechanical alterations result in increased knee abduction and internal rotation angles, increased hip rotation angles, increased hip internal rotation moments, and decreased knee flexion angles. The present study sought to evaluate differences primarily in the frontal plane due to their
implications in injury risk. Our participants demonstrated increased peak knee moments following fatigue in addition to a more vertical limb, which may have significantly impacted loading of the ACL. Further, this study identified differences with respect to limb dominance that may increase the risk of injury. This information may be beneficial for clinicians, trainers, and coaches in establishing injury prevention strategies. Intervention programs should focus on improving bilateral symmetry and kinematics by teaching athletes to cut with a more flexed hip and knee to promote hamstring co-contraction and decreasing the moment of inertia of the body about the foot.

**Practical Implications**

- Post-fatigue, altered mechanics were observed that may place a female athlete at an increased risk of injury.

- Preventative training focusing on proper mechanics in a fatigued state may be beneficial.

- Training protocols should emphasize reactionary cutting drills that involve cutting off both the dominant and non-dominant limbs.

**Acknowledgments**

The authors received no financial support for this research.
### Tables and Figures

#### Table 1

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**Peak Stance**

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Descriptive statistics (mean, standard deviation) for kinematic variables between dominant and non-dominant limbs pre- and post-fatigue at initial contact and peak stance. All variables are measured in degrees.
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Descriptive statistics (mean, standard deviation) for kinetic variables between dominant and non-dominant limbs pre- and post-fatigue at peak stance. External moments measures in Nm/kg.
Figure 1. Interaction Effect of (Limb*Time) for Hip Internal Rotation Angle at Initial Contact.

Figure 2. Interaction Effect of (Limb*Time) for Peak Hip Abduction Angle.
Chapter 4: Summary and Conclusions

The current study presents several limitations with regards to the fatigue protocol, subject population, and testing set up. Though the Yo-Yo IR test has been determined to produce similar physiological effects to that of game conditions, it may vary in its influence on the cutting maneuver due to the significantly decreased performance time relative to actual game play. To induce fatigue, the Yo-Yo IR test, maximum vertical jump height, and heart rate were used and although the individual reported being fatigued and showed decreased performance, further assessments of overall fatigue should be employed. Additionally, only female, collegiate level soccer and field hockey players were used in this study. Future research including a greater number of sports, multiple skill levels, age groups, and both genders would enhance our understanding of the impact of fatigue and the possible effects of limb dominance on injury risk. The lab set-up for testing somewhat decreased the external validity of the study in that it does not reflect true sporting conditions. All athletes tested primarily compete outdoors, meaning the current study tested them on different playing surface conditions and in a restricted space. The decreased space allotted for the cutting maneuver inhibited the participants from reaching top running speeds prior to performing the cutting maneuver off the force plates. The signaling images were created to induce a similar reactionary response to what the participants would experience during a game, however, future studies may increase the validity of this by using actual game footage, or a live opponent for the participants to react to. The current study did not use electromyography during testing, so
neuromuscular fatigue/dysfunction was speculated. Future research may also choose to test interventional training programs and re-test athletes upon completion of these programs.

Prior research has determined that following fatigue, mechanical alterations result in increased knee abduction and internal rotation angles, increased hip rotation angles, increased hip internal rotation moments, and decreased knee flexion angles. The present study sought to evaluate differences primarily in the frontal plane due to their implications in injury risk. Our participants demonstrated increased peak knee moments following fatigue in addition to a more vertical lower extremity posture, which may have significantly impacted loading of the ACL. Further, this study sought to identify changes across the ankle, knee, and hip as well as differences with respect to knee dominance in order to enhance our current understanding of possible alterations that may increase the risk of injury. As a result of this study, it was determined that fatigue impacts mechanics across the ankle, knee, and hip, and together, these altered mechanics place the knee at a greater risk of injury. This information may be beneficial for clinicians, trainers, and coaches in establishing injury prevention strategies, with respect to fatigue and contralateral limb asymmetries.
Chapter 5: References


30. Nordlund, MM, Thorstensson, A., & Cresswell, A.G. Central and peripheral contributions to fatigue in relation to level of activation during repeated maximal


35. Gehring, D, Melnyk, M., & Gollhofer, A. Gender and fatigue have influence on knee joint control strategies during landing. *Clinical Biomechanics* 2009; 24(82-87).


