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The Effects of a Game Simulation on Muscle Activation and Knee Kinematics in Females

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THE EFFECTS OF A GAME SIMULATION ON MUSCLE ACTIVATION AND KNEE KINEMATICS IN FEMALES

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ABSTRACT

Intro: Female athletes experience non-contact ACL injuries at 5 times the rate of male athletes. These injuries occur more frequently at the end of halves and may be associated with exercise-induced fatigue causing knee instability. The purpose of this pilot study was to determine the effect of strenuous exercise on lateral knee movement during the landing phase of a jump. **Methods:** Ten subjects completed both the exercise and the control trial consisting of two 25-min game simulations on a treadmill or on a separate day the equivalent rest. Before, at half time, and immediately following the interventions subjects performed sets of 3 box jumps and vertical leaps. Surface Electromyography (sEMG) was used to assess relative muscle activation (%MVIC) and 2D video analysis to assess changes in Q Angle upon landing from a box jump. Data were analyzed by 2 factor repeated measures ANOVA. **Results:** Power analysis indicated the study was under powered and that 18 subjects were necessary to be adequate statistical power; therefore, results were interpreted with $p \leq 0.1$ as significant. There was no effect of exercise on Vertical leap, a measure of muscular fatigue. However, Q angle increased by 7.4 degrees following completion of the second exercise session (Pre:21.7±2.34 vs Post: 29.2±5.48) ($p=.09$). %MVIC decreased significantly over time for the Gastrocnemius (Pre: 78%±4% vs Post: 66%± 5%, $p \leq .1$), bicep femoris (Pre: 68%± 3% vs Post: 64%±3%, $p \leq .05$) and gluteus medius (Pre: 72%±5% vs Post: 58%±4%, $p \leq .05$). The latissimus dorsi (Pre: 48%±2% vs Post: 41%±3%, $p \leq .05$) and gluteus medius (Pre: 34%±3% vs Post: 29%±2%, $p \leq .05$) muscles were activated later when comparing pre-exercise values to post-exercise results. **Conclusion:** These data indicate that knee instability with exercise may not require muscular fatigue, and that changes are associated with altered muscle activation. The changes in muscle activation timing may reflect compensation for altered muscle activation.

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LIST OF ABBREVIATIONS

ACL.. Anterior Cruciate Ligament

BF.. Bicep Femoris

GA...Gastrocnemius

GM .... Gluteus Medius

LD .... Latissimus Dorsi

MVIC ....Maximum Voluntary Isometric Contraction

RF...Rectus Femoris

VMO .... Vastus Medialis Oblique

CHAPTER 1

AIMS OF THESIS

P1: Anterior cruciate ligament injuries in men and women

P2: Prevalence of non-contact anterior cruciate ligament injuries in female athletes.

P3: The goal is to identify whether fatiguing exercise simulating a game affects the risk of anterior cruciate ligament injury.

P4: A total of 20 female participants will be recruited from the University of South Carolina.

Aim 1: Determine the activation pattern of selected lower appendicular skeletal muscles during the landing phase of a jump

Hypotheses:

1.1: The timing of muscle activation will be altered for selected muscles following a bout of strenuous exercise.

1.2: The “activation” of the quadriceps muscles will increase following a bout of strenuous exercise, while the hamstring muscles “activation” will decrease.

Aim 2: Determine whether strenuous exercise alters the activation pattern of selected lower appendicular skeletal muscles during the landing phase of a jump.

Hypotheses:

2.1: The activation pattern of the biceps femoris, the quadriceps muscles and the gastrocnemius muscles will be altered during the landing phase of a jump from a fixed height following a bout of strenuous exercise.

2.2: A strenuous bout of exercise will result in a reduced vertical jump height.

Aim 3: Determine the effect of strenuous exercise on the valgus knee movement during the landing phase of a jump.

Hypothesis:

3.1: Valgus knee movement will increase upon landing from a jump following strenuous exercise.

CHAPTER 2

REVIEW OF LITERATURE

Introduction

Between the 2004 and 2009 NCAA football seasons over 50 percent of all injuries were to the lower limb of an athlete. The knee alone accounted for 17.1% of all injuries throughout this period. [1] As a joint, the knee appears to only move between flexion and extension. In reality, the knee rotates and moves side to side with every step you take. The stability of the knee joint can be easily altered and may result in damage. [117] The joint is often vulnerable during many athletic maneuvers used in sports such as football, basketball, soccer, and lacrosse. Any movement that includes a plant and twisting motion has been linked to an increased risk of injury to the ligaments and cartilage protecting the knee. [37, 62] Several risk factors have been identified for knee injury, of which some are modifiable and others cannot be modified. Consequently, prevention of injuries through identification of modifiable risk factors and the management of these factors can be potentially beneficial.

Many factors, including fatigue can alter muscular activation and have been linked to increased risk of injury to the knee. Individuals competing in sporting events will experience varying levels of fatigue. This fatigue may cause alterations in muscle activation, and thus result in a decreased level of performance. [107] Fatigue has been shown to decrease an individuals' control of their body movements over time. [4, 118, 122] The decreased control of body movement has been linked to an increased risk of injury due to fatigue.[21, 118, 135] Injuries to the ligaments surrounding the knee are most commonly seen during a fatigued state and consist of a rupture or a partial tear. [17, 36, 48]

Anterior cruciate ligament (ACL) injuries can be one of the most devastating injuries to the career of an athlete. Exacerbating the situation is the fact that 69 percent of all individuals who suffered non-contact ACL injuries are unable to return to their pre-injury performance levels. This type of injury is not limited to a single population or even a single sport. There are over 200,000 ACL injuries in the United States alone each year. [84] Approximately 70 percent of these ACL injuries occur during non-contact scenarios.[51, 52] Time periods of high risk for non-contact ACL injuries are negative acceleration, cutting, jumping, and any obstacles that can alter movement patterns. Female athletes are between 2 and 4 times more likely, depending on the sport, to rupture their ACL than their male counterparts. [40] Fatigue late in games and altered motor control patterns are thought to be potential injury risk factors. Following ACL surgery, the typical patient will feel close to normal within 6 to 12 months following surgery. [7, 100]

This literature review will explore possible causes and effects of ACL injuries for athletes in more depth as well as the financial and performance losses that can result from ACL ruptures and partial tears. An ACL injury is not just a short-term inconvenience; it has lasting detrimental effects that will limit individuals. It is possible to have varying degrees of ACL injury, but for the purpose of this review we will be focusing on ACL ruptures specifically. By furthering our understanding of how and why non-contact ACL injuries occur, we can hopefully find a way to reduce the risk of ACL injuries for all individuals.

The Anatomy of the Knee

The knee joint, also known as the tibio-femoral joint, is comprised of bone, cartilage, and ligaments. The tibia and femur are the two main bones that meet to form the knee joint. These bones are responsible for carrying the majority of the bodily weight, with the femur being the strongest bone in the body. Cartilage within the knee is located on the ends/caps of the femur and tibia. Cartilage allows for the joint to flex and extend smoothly without pain. Ligaments are responsible for maintaining stability and connecting bone to bone. There are four ligaments in the knee that help maintain stability and mobility of the joint. These consist of the anterior and posterior cruciate ligaments, and medial and lateral collateral ligaments. Injury to one of these ligaments will cause joint instability and can increase risks for further damage. These components are all potential locations for injury to occur, but this review will be focused on the anterior cruciate ligament. The anterior cruciate ligament is one of the most important ligaments for sports performance, in that it plays a key role in knee stability. Stability is crucial during athletic motions that require positive and negative acceleration. The ACL is comprised of dense regular connective tissue with a multitude of rows of fibroblasts and type I collagen. The ACL itself is between 22 mm and 41 mm in length and is 7 mm to 12 mm wide. [6] The cross-sectional size and shape of the ACL will change with movement, and varies along its' length (proximal end is 34 mm^2, 33 mm^2 at the mid-proximal point, 35 mm^2 at the mid-substance level, 38 mm^2 at the mid-distal points, and 42 mm^2 distally). [47] The ACL originates from the anterior aspect of the tibial plateau and inserts on the lateral femoral condyle. Functionally the ACL is responsible for preventing anterior translation of the tibia, as well as assisting in prevention of tibial rotation. When the quadriceps muscle group is contracted, an anteriorly directed force is exerted from the patellar tendon on the tibia. This is present between 0 and 60 degrees of knee flexion, causing load to be placed on the ACL. When above 60 degrees of knee flexion there is an unloading of the ACL. [19, 50] When the hamstrings muscle group is contracted, a posteriorly directed force is placed on the tibia. This force is exerted throughout the entire range of motion, but is greater at higher levels of knee flexion angles leading to a decreased amount of force on the ACL.[19, 50]

Demorat et al. (2004) collected data that directly measured forces on the anterior cruciate ligament before a tear or rupture occurred. Data, in cadavers, showed on average that it took 4,500 newtons of quadriceps contraction force in order to see partial tears or complete ruptures in 6 of the 11 knees tested. [30]. Per Hootman et al. (2007), out of the schools that participated, it was determined that there were on average 313 reported ACL ruptures per year in collegiate athletics. If the sample population represents 15 percent of the total 15 sport population, then on average there should be 2,000 ACL ruptures per year throughout the 15 studied sporting activities. [54] It has been shown that approximately 7,000 high school female basketball players injure their ACL each year across the United States.[40] The current literature shows on average, female athletes in lacrosse, soccer, and basketball are more likely to suffer an ACL injury compared to their male counterparts.[82, 104]

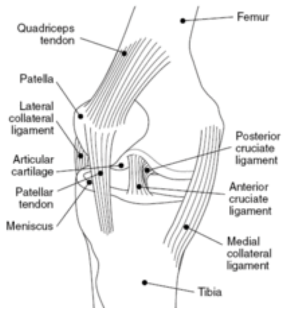

Figure 2.1 Ligaments and tendons of the tibiofemoral joint.[71]

There are three main degrees of injury for ligaments in the body. A Grade 1 ligament injury is mild in nature and consists of a slightly stretched ligament. When a ligament is stretched to the point at which it becomes loose it is referred to as a Grade 2 tear. This level of injury is moderate in nature and is often referred to as a partial tear. A rupture, or Grade 3 tear, occurs when the ligament is split into two pieces. With a Grade 3 tear, the joint is no longer stable and leaves the joint susceptible for further injury. Therefore, an ACL rupture is classified as a complete tear of the ACL into two individual pieces. The lack of support from the ACL will lead to instability of the knee as a whole.

Repercussions of an ACL Rupture

An ACL rupture leads to substantial costs, both physically and financially, for an individual and their family. Individuals who rupture their ACL often struggle returning to the field and performing at the pre-injury level, while others struggle to pay the bills following surgery and rehabilitation. Others struggle with the psychological side of the equation, with lack of confidence in the leg. This lack of confidence in the injured leg will lead the individual to rely more heavily on the good leg. By increasing the reliance on the good leg, it may open up the risk for many overuse injuries of the uninjured limb.

An ACL injury will lead to instability of the knee and muscular atrophy across the entire limb. Muscle atrophy is the loss of muscle fiber contractile proteins in the effected limb, which results in a reduction in the maximal force output. Furthermore, immobilization of the limb will lead to alterations of neuromuscular control that require motor patterns to be relearned. [110] Following ACL injury, or reconstruction surgery, the affected limb is used less due to pain and a decreased stability of the joint, which will lead to increased atrophy. Atrophy plays a large role in the decreases in performance seen in many individuals. Due to the loss of muscle mass from disuse, a decrease in force production often results. Studies have shown that there is approximately a 50 percent decrease in concentric average peak force production. [55, 85] Eccentric loss of strength is consistent with this finding and shows anywhere between a 23 percent decrease and a 50 percent decrease in force production[53, 63, 99]. The goal of rehabilitation for ACL injuries is to return strength and stability to the knee. This is accomplished through a use of regimented protocols to teach motor patterns and stimulate muscle hypertrophy. A study by Carey et al (2006) followed NFL running backs and wide receivers over a 5-year period that had suffered an ACL injury. They found that on average the athletes returned to sport the following season with a 30 percent decrease in on-field performance. [20] This decrease in performance can potentially lead to a loss of earning potential due to early termination of career for professional athletes. One case where ACL injuries prevented the return of an athlete can be seen in Marcus Lattimore. He was a top football player at the University of South Carolina, but unfortunately his career was full of major injuries. He ruptured his ACL in his left knee in 2011 and after his return for the 2012 season he dislocated his right knee and tore every ligament in the knee. His injuries were from full contact hits during football games, but he shows the negative impact on future performance due to this type of injury. He decided to cut his career short from the inability to perform at pre-injury levels and the recurrent pain associated with the injury.

Some individuals struggle with the psychological aspects when trying to return to sport following ACL injury. A study by Arder et al. (2014) reported 60 percent of participants had not returned to sport between 1 and 7 years. Of this 60 percent, it was determined that 28 percent had not returned to competition due to lack of trust in the knee, 24 percent had not returned from fear of a new injury, and 22 percent had not returned due to poor knee function. Recovery time for most individuals is 1 year; at this point post-injury strength has met or nearly met pre-injury levels. However, the time lost due to injury may have financial repercussions for the injured individual.

Finances play a large role as to the outcomes many individuals experience. ACL reconstruction surgery, for an individual with health insurance, often costs on average $4,500 or $6,000 depending on whether the surgery was allograft or autograft respectively. The autograft surgery costs more mainly due to longer surgery time needed. This autograft surgery requires the surgeon to take the graft from elsewhere in the body, usually the hamstring or patellar tendon. This requires an additional cut and additional time to prepare the graft correctly. This cost covers all expenses for the surgery, hospital stay if needed, and medications, however this does not include the pre-operative doctors' visits or any of the rehabilitation that will be needed before or following surgery. Mather et al. (2013) determined that a patient who had ACL reconstruction surgery, on average, would pay $38,121 over their lifetime. On the other hand, a patient who opted for only rehabilitation paid $88,538, on average. These costs reflect the acute expenses of surgery and rehabilitation, but do not consider the future side-effects of this traumatic injury. Approximately 27 percent of the financial costs are spent within six years of injury/surgery, with the remaining cost spent over the remainder of the patients' life. [76] Some of this cost can be explained by long-term disability due to the instability of the knee, but the majority is due to the development of knee osteoarthritis.[76]

Many patients typically think about the acute impacts of an ACL injury, but many of the real issues occur later in life. The main long-term detriments consist of the development of osteoarthritis and progressive cartilage damage. Literature has shown a wide range for individuals who will develop osteoarthritis of the knee within 10-15 years of ACL surgery. Depending on the severity of injury, additional structural damage, and quality of repair the prevalence for developing osteoarthritis ranges anywhere between 10% and 78%. [74, 95, 124] Osteoarthritis can cause aching, stiffness, and a grinding sensation when the joint is moved. The joint tends to feel better when at rest, compared to the pain and stiffness typically experienced during movement. The feeling of less pain while at rest encourages a more sedentary lifestyle, which can promote the development of other negative health issues such as obesity and heart disease. Some patients try to get cortisone shots for temporary relief, but these are just temporary fixes. A person with insurance can expect to have between $9,800 and $22,000 annually billed to their insurance depending on if their osteoarthritis is mild or severe, respectively. [76] Physical rehabilitation has been shown to partially relieve symptoms from osteoarthritis and promote a healthier lifestyle. [31] Despite the benefits from rehabilitation, the damage to the joint has already been done. The majority of individuals choose to have a knee arthroplasty due to pain and suffering from the osteoarthritis.

Rehabilitation

The rehabilitation process following ACL reconstruction surgery is long and difficult. The process often takes a full year to return to a level close to pre-injury performance levels. The patient cannot begin running activities until 6-8 months following surgery. Muscle atrophy and neuromuscular changes cause a 20 percent reduction in concentric leg activation force 6 months following surgery compared to pre-injury levels, with a 10-15 percent reduction at the 1-year mark.[7] This is commonly due to muscular atrophy or an inability to activate the muscle fibers. The inability to activate the muscle fibers is likely due to the inflammation found post-surgery. This weakness can potentially put the individual at increased risk for a second ACL injury due to instability caused by muscle weakness. Many physicians use the limb symmetry index in their return to sport protocols. The limb symmetry index compares the affected limb to the unaffected limb. The limb symmetry index is completed by performing 4 single leg hop tests for each individual limb. [108] A percentage can be calculated to determine the percent deficit the affected limb has compared to the unaffected limb. [108] Many studies, such as the one by Adams and colleagues (2012), found that limb symmetry indices of 90 percent are thought to be the golden number for determining normal limb symmetry in quadriceps strength. They determined this number by implementing a Knee outcome survey and comparing the age and sex matched norms on the International Knee Documentation Committee 2000 Subjective Knee Evaluation Form to the patients' strength levels.[2] The majority of rehabilitation protocols for ACL patients focus on strengthening the hamstring and quadriceps muscles. By strengthening these muscles, it is likely the patient will have greater knee stability. However, if we can find a way to prevent non-contact ACL injuries then we prevent the need for costly ACL reconstruction surgery and rehabilitation.

ACL Injury Prevention

Many sports, specifically football and men's lacrosse, are filled with injuries due to contact situations. [77, 82] ACL injuries due to contact are unlikely to be prevented, but by raising awareness and furthering our understanding of the mechanics behind ACL injury we can reduce and possibly prevent the non-contact ACL injuries. If non-contact ACL injuries can be prevented, individuals will have a better quality of life and will be able to maintain their careers for an extended period. The literature supports four main categories of non-contact ACL injury risk factors: anatomical, environment, hormonal, and biomechanical. [4, 42, 52, 121]

Risk Factors for Non-Contact Related ACL Injury

There are many different factors that play a role in non-contact ACL injury in both males and females. The majority of research supports four main categories of risk factors: anatomical, environmental, hormonal, and biomechanical. [4, 46, 52]

Anatomical Risk Factors: Certain anatomical factors such as alignment of lower extremities, the amount of muscle present, foot pronation, and the level of laxity found in the joints can all predispose an individual to ACL injury. These factors will all cause changes affecting the kinetic chains of individuals' movement patterns that may lead to increased risk of injuries. However, the evidence is not clear and the literature has shown mixed results. A few studies have begun looking at femoral notch size and ACL size itself to determine if these play a role in probability of injury. [6, 47] Multiple studies have reported that females consistently have greater foot pronation, joint laxity, tibial torsion, and increased Q-angle. [8, 40, 89] The Q-angle is determined by drawing a line from the anterior superior iliac spine to the middle of the patella. The angle is formed by connecting this line to a line running along the tibia of the individual. Many studies have found that most "normal" females have a Q-angle between 13 and 18 degrees. Sprains of ligaments occur when the length of ligament exceeds normal values. After resting and letting ligament heal, it will be shorter and stiffer, so stretches and exercises will be needed to help reduce the stiffness and regain full range of motion. No literature was found pertaining to the original length or thickness of an ACL predisposing an individual to injury, which shows that further research is needed to understand the ACL.

Biomechanical Risk Factors: Biomechanical factors have been associated with common alignments and trends seen in the sagittal, coronal, and transverse planes. Previous research has shown significant differences between those with and without a history of ACL injuries. The nine participants who had a history of ACL rupture had significant differences in joint loading and landing mechanics when compared to the 196 who did not have an ACL rupture.[51] The nine participants had 8-degrees of greater knee abduction, 20 percent high ground reaction force, and knee abduction moment 2.5 times greater. [51] Hewett et al. (2005) discovered that females, with no history of ACL injury, landed with a similar knee flexion angle compared to females with a prior ACL injury. Research has shown that a knee abduction moment of 25.3 Nm is likely the threshold for risk of ACL injury. [89] It was found that a knee abduction moment above 25.3 Nm is associated with a greater risk for ACL rupture. [89] The research on factors in the sagittal plane mainly focus on anterior shear forces seen during knee flexion. Mclean et al.

(2004) showed that the peak anterior drawer force in his model was not sufficient to exceed the required force for ACL rupture. The motions and torques in the coronal plane may explain many of the gender based differences in ACL injury rates. Ford et al. (2003) showed that female athletes had a greater knee abduction moment immediately prior to cutting than males. Many other studies found supporting data that females had greater knee abduction moments and significant differences in contraction of abductors and adductors compared to males. [11, 40, 51, 87, 134] The transverse plane primarily focuses on the internal and external rotation motions as mechanisms for ACL injury. [78] Besier et al. (2001) analyzed the sidestep cut under both planned and unanticipated conditions at two different angles. The data showed both increased internal and external rotation knee moments during the unanticipated conditions. This finding supports the idea that lower extremity muscles will activate at different levels between planned and unanticipated conditions. [13] Besier et al. (2003) showed a 10-25 percent increase in muscle activation during unanticipated movements. Further research is needed to explore which movement planes create the greatest risk for ACL injury.

Environmental risk factors: The studies involving environment factors typically focus on athletic events, but some can be translated to the general public. Many studies have looked at three main factors including the effects of type of playing surface, type of shoe/cleat, and player positioning. The relationship between surface and shoe is one factor that can be generalized to the public. A high level of friction between the shoe and surface has been determined as a major contributor of ACL injury. [112] Performance is typically better when the friction between shoe and surface is higher. [98, 112] Athletes must then determine if the performance benefits from high friction are worth the increased risk of injury to lower extremities. Scranton et al (1997) analyzed noncontact ACL injuries across 5 seasons in the NFL by examining the relationship between playing surface, shoe type, and playing conditions. The authors determined that a greater percentage of ACL injuries occurred on natural grass than on artificial turf. [112] Among all ACL injuries within the participants, 47.5 percent occurred on game days, even though they had a five times greater exposure to practice situations. [112] More than 95 percent of all ACL injuries occurred under dry playing conditions. [112] Orchard and Powell (2003) examined the relationship between lower limb sprains, the playing surface, and the weather conditions. Natural grass showed a reduced risk of significant knee sprains when compared to synthetic turf. [98] The results showed a lower risk of significant knee sprains and ACL injuries when cold weather was present and the event took place in an outdoor stadium. [98] The authors concluded that cold weather and a natural grass field was associated with lower ACL injury risk due to the reduced shoe-surface traction. [98] Olsen et al. (2004) examined the video evidence of injury mechanisms for ACL injuries during handball sporting events. The data showed more ACL injuries occurred on synthetic, rubberized indoor floors than on wooden floors. [97] This section shows the importance of understanding exact environmental risks and determining a plan to reduce these risks for all individuals, whether promoting natural grass or certain cleats.

Hormonal risk factors: Hormones have been tied to the risk of ACL injury in many previous studies. The literature has shown that fibroblasts within the anterior cruciate ligaments have estrogen and progesterone receptors associated with them. [52, 73] Estradiol inhibits collagen synthesis in cultured fibroblasts from female ACL tissue. [16, 73, 111] These alterations of collagen levels have been shown to decrease the strength of the ligament. [16] Samuel et al. (1996) found that the hormone relaxin is responsible for a decrease in the tension of soft tissues. Relaxin, a peptide hormone that is primarily secreted and produced by the ovaries in females may contribute to joint laxity in females. [132] Relaxin has been shown to have a collagenolytic effect on ligaments due to the release of collagenase upon activation of relaxin receptors on fibroblasts. [43, 123, 125, 126] Although relaxin is mainly responsible for changes during pregnancy, in non-pregnant women it reaches highest concentration between ovulation and the onset of menstruation. [18] The main function of relaxin, is to relax ligaments in order to create space for a fetus. [33] Since relaxin levels are greatest between ovulation and menstruation, the ACL may be more relaxed at this point in the menstrual cycle, but further research is needed to confirm this. [33, 130, 132] Normal non-pregnant women have been shown to have a serum relaxin concentration of 3.6 pg/mL. [131] Pregnant women have shown greatest relaxin concentrations over the first 15 weeks following conception. [3, 68] The peak relaxin concentration rises early during pregnancy and peaks around week 10 or 11 of the pregnancy. At the peak, pregnant women have reported average relaxin concentrations as high as 1200 pg/mL. [3, 68] This shows that pregnant women have much greater exposure to relaxin, so more research is needed to confirm that small concentrations can indeed cause structural changes to the ACL. Studies have shown that increased estrogen lead to decreased tensile strength in ligaments in animal models. [64] Animal models have also shown, upon administration of relaxin, a significant weakening of the ACL in load to failure testing was seen. [32] The findings from the animal studies support a possible synergistic collagenolytic effect on the ACL, between relaxin and estrogen levels in females, that may lead to increased risk of rupture. The majority of research on the effect of the menstrual cycle on ACL has returned with conflicting results. Wojtys et al. (1998) discovered that there was an increase in noncontact ACL injuries during the ovulatory phase, while also observing a decreased number of ACL injuries during the follicular phase of the menstrual cycle. Slauterbeck et al. (2002) and Moller-Nielson (1991) both found that the phase with the highest number of ACL injuries and serious injuries, respectively, was the luteal phase. Per Myklebust et al. (2003), the follicular phase has the greatest number of ACL injuries. The exact influence of hormones, specifically estrogen and relaxin, on non-pregnant ovulating women is not well understood, and needs further investigation. Many high school and collegiate female athletes are exercising at high intensities and are not eating appropriately to maintain their health. A combination of low body fat, high energy expenditure, and low caloric intake have been associated with amenorrhea. Amenorrhea is defined as the absence of one or more menstrual cycles. A study done in the Netherlands reported 9.8 percent of ballet dancers in their study had amenorrhea. [39] Pettersson et al. (1973) determined that 4.4 percent of participants developed secondary amenorrhea due to smoking or oral contraceptive use. Collegiate athletics requires athletes to be in peak condition to optimize performance. This results in the female athletes pushing their bodies to their limits. I would expect these factors would lead to an increased prevalence of amenorrhea, but further research is required in order to confirm this thought.

The degree of fatigue is another major risk factor for ACL injuries. Fatigue opens an individual to increased risk of injury due to a decreased control of movements. [81] You can train to delay the onset of muscular fatigue, but eventually fatigue will affect everyone. This is especially common in the latter portions of competitive events. Under a fatigued state an athlete can expect to see decreased muscular strength, decreased reactions, and decreased mental function. [35, 41, 80, 107] These changes can all lead to increased degrees of the previously discussed risk factors. [46, 118, 122] Rahnama et al. (2006) and Greig et al. (1985) both focused on the detriments of muscle activation and strength due to fatigue.

Muscle Activation

Muscle activation has been a topic of much interest over the years for a broad variety of studies. Muscle activation begins in the brain. An electric signal is passed through nerves until it reaches the desired muscle. If the stimulus is sufficient to surpass threshold, then a cascade of events take place to elicit a muscular contraction to accomplish the desired task. The measurement of muscular activity is often done using an electromyography (EMG) machine. These machines require an electrode to be placed on the skin or in muscle belly itself with fine wire electrodes. The EMG will allow the user to determine when muscle activation initiated and terminated, as well as the magnitude of activation. Surface electrode use leads to limitations due to accuracy of placement, body composition, narrowing down correct muscle signal. Increased levels of adipose tissue between the muscle and electrode has been shown to reduce the EMG reading for the activated muscle. [69]

One of the most interesting uses of muscular activation analysis is with injury prevention. Many studies have investigated the mechanisms for injury throughout the body by studying the amplitude/strength of activation at certain time points during sporting events. An initial maximum volitional isometric contraction (MVIC) is needed in order to compare effects of pre and post interventions. By comparing to initial MVIC a percentage can be calculated for comparison. When analyzing muscular activation over a period of exercise data has shown that muscular activation amplitude increases as speed and intensity of exercise were increased. [106, 120, 127] In order to increase speed or force output an increase in muscular recruitment and activation is required. [128]

Many of the studies that used non-invasive electrodes have found contradicting evidence when looking at the effects of fatigue on muscular activation. A study by Greig et al. (1985) found that lower limb muscle EMG activity increased after fatiguing exercise. Wojtys et al. (1996) reported that EMG activation of the hamstring and quadriceps actually decreased after a fatiguing exercise. Miller et al. (2000) found no significant differences in hamstring or quadriceps activation as duration/number of repetitions increased. The nature of these contradictions shows that further research needs to be conducted in order to further understand the ramifications of these changes.

Multiple studies investigated the effects of exercise speed and rate of contraction on the levels of muscle activation. [38, 45, 58, 127] The authors investigated the rectus femoris, tibialis anterior, biceps femoris and the gastrocnemius during flexion and extension exercise while seated. These studies consistently found the amplitude of the muscular activations increased as the speed of exercise increased. At the faster speeds, the hamstring muscles had to activate earlier and more often in order to increase negative acceleration towards the end of each lower limb motion. [38] Further research is needed to translate these results to running scenarios. Assuming the knee can maintain stability, the results will likely show similar muscular responses. The results from Fleming et al.

(2001) show the possibility of an alteration in timing or order of muscle activation, which will need to be confirmed with further research. The rectus femoris, tibialis anterior, and biceps femoris muscles showed a decrease in amplitude as the duration of exercise increased. A decreased muscle activation as duration of exercise increases leads to further questions about game duration and the effects of fatigue. The inability of muscles to stabilize the joint later in games, will lead to an increased risk of injury during latter stages of a game. The gastrocnemius muscle did not show any significant changes. Some studies have shown a change in gastrocnemius activation with exercise. The contradictions between studies may be attributed to type of exercise, duration, or another unknown factor. Further research is needed to clarify what consistently causes a change in gastrocnemius activation.

A variety of exercise protocols exist to assess the effects of fatigue on muscle activity. Many theorize that different results will be seen depending on whether the exercise bout is high intensity short duration or long duration and low intensity. Many commonly accept the fact that significant differences in muscle activation can be seen between eccentric, concentric, and isometric muscular contractions. [10, 44, 105, 120] Following this accepted belief it is likely that a reduction in muscular activity would be seen with increased duration, force output, or change in type of contraction. This decrease in muscular activity would be due to a decrease in muscle torque/force output, which is often paired with fatigue according to studies. It is expected that the muscles involved with knee flexion will show a greater decrease in output/activity than the muscles involved with knee extension. Sporting events require many bouts of cutting and jumping motions, which require greater amounts of negative acceleration to prevent injury from overloading a joint. An increase in negative acceleration is mainly associated with the muscles that cause knee flexion. With a decrease in the hamstring activity, with little to no change in quadriceps activation, the ratio between hamstrings to quadriceps strength will see a significant decrease. Recent research shows hamstring to quadriceps strength ratio as a major risk factor for lower extremity knee injury. Per Ivanenko et al. (2004), there are five basic muscle activation patterns for human locomotion. Patla et al. (1985) suggested only a few basic activation patterns are utilized, and can be combined appropriately to produce the observed muscle activations. Several studies reported similar muscle activation patterns are observed across subjects with different weight, height, and body mass distribution. [23, 28, 96, 101] Per Lewis et al. (2009), the order of muscle activation was the same across all female participants for a prone hip extension exercise. The data suggests that the magnitude and timing of activation may be altered based on verbal cues. [72] Muscle activation is important in establishing normal knee kinetics and kinematics for all individuals. If we can further our understanding of muscle activation during various movement patterns, then the knowledge of injury mechanics may be increased.

Sigward and Powers (2006) compared knee kinetics, kinematics, and muscle activation between male and female athletes. Females were shown to have a greater average quadriceps EMG during periods of negative acceleration compared to their male participants, 191 percent to 151 percent of MVIC respectively. The data suggested that during early negative acceleration phases 80 percent of the females showed an adductor (valgus) movement, while only 40 percent of the males showed the same adductor movement. [113] A greater quadriceps and adductor moment will both lead to increased stress on the knee, specifically the ACL. This increased stress moment will lead to an increased risk of rupture.

The timing at which muscles are activated during an athletic movement could alter force outputs and performance. By activating differently at resting and fatigued states, there could be greater stress on the body which opens the possibility for injury. Studies have shown differences between genders regarding the timing of muscle activation during athletic performances. [12, 13, 27, 87, 109, 127, 128, 134] Huston and Wojtys (1996) reported a slower response of hamstring activation to anterior stress on the ACL in female athletes. If this is the case, then the tibia in females can shift further before contraction of hamstring muscle compared to males. On the contrary, Cowling and Seele (2001) showed that female hamstring muscles were activated earlier than male hamstring muscles prior to landing. Cowling and Steele suspected that the male activation pattern led to a greater synchrony of muscle, which resulted in a more controlled joint loading. In females, the vastus medialis oblique (VMO) has been shown to contract less frequently than the lateral muscles of the quadriceps. [87] This decreased activation will result in greater instability of the knee, thus causing increased stress on the ACL. Besier (2001) and Sigward et al. (2007) found that there was an increase in knee varus and knee valgus during unanticipated maneuvers. The data showed that lower extremity muscle activation varied significantly between pre-planned and unanticipated conditions. [13] These unanticipated conditions caused a 10 to 25% increase of muscle activation in male athletes immediately prior to initial contact. [13] Further research is needed to see if females respond the same way as males. Zazulak et al. (2005) reported greater rectus femoris muscle activation in female athletes during the pre-contact phase of a landing task. This increase in quadriceps activation, combined with low hamstring activation, can contribute to a decrease in energy absorption during landing. [134] This decrease in energy absorption will result in an increase ground reaction force, which has been shown to be associated with ACL injury. [134] These studies all show a significant difference between male and female athletes. In summary female athletes are at a greater risk for ACL injury than males during normal exercise conditions.

Although Wojtys et al (1996) suggested that the timing of muscle activation did change with fatigue, they did not find any change in the order of activation. They found an increased pre-motor phase post fatigue inducing protocol. [128] There is little research on changes of the order of muscle activation due to fatigue; therefore one of the goals of this study is to further explore any changes in order of activation due to fatigue.

No coach or athlete wants to see an injury occur during any sporting event. Unfortunately, it may not be possible to prevent all injuries, but we can further our understanding of when players are at the highest risk of injury. Studies have looked at the timing of ACL injuries across a multitude of sports, and found that the majority of ACL injuries occurred towards the end of halves/games when the athletes are suspected of having significant fatigue. A study by Harris et al. (2013) reported 40 percent of ACL ruptures in the NBA occurred in the fourth quarter, with 62 percent of all ACL ruptures occurring in the second half of a basketball game. [48] Another study by Bradley et al. (2002) looked at 209 ACL injuries across the NFL and discovered these injuries occurred most frequently in the second quarter of a game. Erickson et al. (2014) reported nearly 60 percent of ACL ruptures in NFL quarterbacks occurred during the second quarter, instead of 14 percent in each of the remaining quarters.

Fatigue

In order to discuss the effects of fatigue, we must first define fatigue. Many generally define fatigue as a decrease in the ability to produce force. [15] While this definition is scientifically correct, there are other researchers that would prefer a more informative definition. They define fatigue as a force output that is less than the expected response, for a certain level of activation or stimulus. [9, 14] This definition allows us to compare any changes in output that are often seen during sustained exercise. Much of the recent research has been focused on whether the decrease in performance is due to central or peripheral factors. For central fatigue many believe that the muscles are still capable of generating a greater force output, but the central nervous system is unable to provide a sufficient stimulus to elicit the desired response. [41, 119] Central fatigue has been linked to changes in neurotransmitters such as serotonin, dopamine, and noradrenaline. Newsholme et al. (1987) came up with the Central Fatigue hypothesis that proposed an increased level of serotonin in the brain would result in feelings of lethargy, sleepiness, and negative mood. Davis et al. (1997) suggested that the interaction between serotonin and dopamine was more likely the cause of central fatigue. A lower ratio was linked to increased performance, while a high ratio elicits lethargy while decreasing motivation. These changes result in a decreased level of performance. On the contrary, peripheral fatigue is often associated with the muscles' inability to respond with the same degree of output, as previously seen, due to some bout of exercise.[75] This decreased muscular response is likely due to one of many reasons. Excitation-contraction coupling is used in order to produce force or movement. Based on the definition of fatigue above, fatigue can be caused by any interruption in this coupling cycle resulting in a decreased ability to produce force. Past research has shown that peripheral fatigue is related to the force-calcium relationship and the reduction in muscle activation.[5, 24, 75] More specifically, it has been debated whether fatigue results from a lower free calcium concentration at a given stimulus, or rather from a decrease in the sensitivity of any of the contractile proteins at specific concentrations of calcium. [5, 24] During a fatigued state individuals no longer have full ATP stores, which limits the amount of ATP that is available throughout the body. A decreased availability will lower the gradient and result in an accumulation of ADP and inorganic phosphate molecules. These molecules will interfere with ATP binding, resulting in a slower separation from the myosin receptors. A low level of ATP will affect the body centrally by allowing for a lower frequency of stimulation. The neurons throughout the body are forced to fire at a slower pace due to the low levels of ATP resulting from fatiguing exercise. Lambert et al. (2002) found high intensity resistance exercise mainly leads to peripheral fatigue throughout the body. The literature is inconsistent on the relationship between intensity of exercise and the causation of central fatigue. One hypothesis is that long duration, low intensity exercise will elicit central fatigue, while short duration, high intensity exercise elicits peripheral fatigue. [133] Central and peripheral fatigue may cause different effects on muscle activation. If the nervous system fatigues (central fatigue), then would be more likely to see changes in the pattern of activation or the percentage of the muscle that is activated. Both central and peripheral fatigue should show changes to the magnitude of muscle activation.

Data has only shown one significant differences in landing kinematics between a basketball game and laboratory fatigue protocol. [40] Both protocols led to a significant increase in knee internal rotation, but the laboratory fatigue protocol additionally caused external rotation of the knee. The basketball and squat/drop landing protocols both resulted in significant knee adduction. [40] This data shows that real games and laboratory protocol can both elicit significant alterations in internal rotation of the knee and adduction. The participants need to be observed closely and the protocol designed appropriately to avoid extra external rotation of the knee when using a laboratory setting.

Per Wojtys et al. (1996) , fatigue of the hamstring and quadriceps muscles caused an increased level of anterior tibial translation. The increased anterior tibial translation will exert excess force on the ACL and may further increase the risk of injury. The hamstring muscle specifically plays a great role in preventing the anterior shift of the tibia. [128] Fatigue of muscles surrounding the knee joint will result in greater instability and control of the knee. Both central and peripheral fatigue have been shown to have similar detrimental effects.

Conclusion

In summary, anterior cruciate ligament injuries are one of the most common lower extremity injuries. Between all ACL injuries approximately 70 percent occur during non-contact situations. [51, 52] Female athletes are between 2 and 4 times more likely to suffer an ACL injury compared to males. [40] Fatigue and a change in muscle activation are thought to be two main components that lead to many non-contact ACL injuries in sports. Fatigue late in a game will lead to a decrease in muscular force output, which will cause a decreased control of body movements. [21, 59, 107, 118, 122, 135] By possibly changing the order or timing of when muscles are activated, the innate safety mechanisms for each individual may be altered. Muscles will often activate in order to prevent injury when they sense high levels of tension. A change in timing of activation due to fatigue may not allow the muscle to activate fast enough during a time of high tension. [93, 106, 127] This study will attempt to determine whether fatigue can elicit changes in the order or timing of muscle activation.

CHAPTER 3

MANUSCRIPT

METHODS

The overall purpose of this study is to investigate the effects of exercise fatigue on the risk of anterior cruciate ligament (ACL) injury by examining differences in kinematics, kinetics, and surface electromyography during the landing phase of a depth jump. Data will be collected from participants while completing a depth jump from an 18-inch box. Participants will use the same preferred footwear throughout the entire experiment. The game simulation protocol is fatiguing exercise, but does not guarantee that all individuals will be equally fatigued. Some participants may experience less fatigue, which may result in decreased alterations.

The study consists of the participants performing three depth jumps and vertical jumps for baseline measurements, followed by a game simulation protocol. Immediately following the first exercise protocol, the participants will perform three additional depth jumps and three vertical jumps for the halftime data collection. After the completion of the second exercise protocol, the participants immediately performed three depth jumps and vertical jumps for post-exercise data collection.

The third chapter presents the methodology used to address the purposes of this study with the following sections: (a) participants and setting, (b) instrumentation, (c) design and procedures, and (d) statistical analysis.

Study Design

In order to gain a more thorough understanding and to explore the aspects discussed in the literature review, this study will implement a repeated measures design, with randomization within each participant. Each participant, willing to do so, will serve as both a participant and a control. The control session will consist of sedentary tasks in order to prevent the onset of fatigue.

Participants

Ten active females will be recruited to participate in this research study. Due to the increased risk of ACL tears in females, as explained in the literature review, only females will be recruited for this study. In order to qualify for participation in this study, individuals must be between the ages of 18-30 years and have no current limitations that would inhibit them from performing the game simulation exercise protocol. The participants must participate in moderate to vigorous cardiovascular exercise for 4 or more hours each week. Participants must have no prior history of ACL tears, and no lower extremity injuries in the previous 6 months.

Setting

All testing and data collection will occur in the Solomon Blatt Physical Education Center at the University of South Carolina (1300 Wheat Street, Columbia SC 29208). All equipment and data collection will take place in Room 113 of the Blatt Center. A True Fitness treadmill will be used for the fatigue inducing protocol. A depth jump exercise has been chosen for measurement due to the ability to standardize the test for all participants and maintain safety for the participants.

Instrumentation

Two-dimensional Kinematics:

A Logitech C922 high speed HD video camera, as seen in Figure 3.1, was used to collect two-dimensional video to allow for kinematic analysis of the ankle, knee, hip, and pelvic girdle during each repetition. Seven retro-reflective markers, as seen in Figure 3.2, will be placed on anatomical landmarks described in Table 1 with double sided tape. From the captured video, the joint angles will be calculated using Dartfish (Team pro version 7.0) software. The angular data will all be compared pre and post performance of the game simulation exercise protocol in order to determine valgus and varus of the knee.

Figure 3.1. Logitech C922 High Speed HD Camera.

Figure 3.2. Reflective markers.

Table 3.1. Reflective marker locations

Marker Name	Location	Segment
TOE	Lateral point of the fifth metatarsal	Toe/Foot
MALL	Lateral malleolus	Ankle
TIB	Lateral point of Tibiofemoral joint	Knee
FEM	Neck of the femur	Upper leg
AC	Acromioclavicular Joint	Shoulder
ELB	Lateral aspect of humeral-ulnar joint	Elbow
CLAV	Sternoclavicular joint	Chest

Figure 3.3. Electrode placement

Surface Electromyography (sEMG):

sEMG analysis used to quantify activity of muscles, and used to determine timing of contraction and relaxation pre and post fatigue treatment. All measurements will be taken in the dominant leg for each individual. Lower leg muscular activity of the bicep femoris (BF), vastus medialis oblique (VMO), rectus femoris (RF), gastrocnemius (GA) will be obtained. The latissimus dorsi (LD) and gluteus medius (GM) data will also be obtained for kinetic chain analysis. Electrode placement can be seen in Figure 3.3, and all data will be collected using self-adhesive electrodes (Figure 3.5). The sEMG leads were linked to a Noraxon DTS Wireless receiver (Figure 3.4). A Noraxon DTS wireless transmitter (Figure 3.5) was linked to the receiver to collect sEMG data. The software utilized for data collection and processing was the Noraxon DTS wireless sEMG system. The sEMG will be sampled at 1000 (HZ). Post processing will include full wave rectification and a finite impulse response filter. sEMG data will be presented as percent of maximum volitional isometric contraction (%MVIC). Peak sEMG will be analyzed from the point where the 2nd foot terminates contact with the box and point where acceleration is equal to 0.

Figure 3.4. Noraxon DTS Wireless System

Figure 3.5. Noraxon DTS wireless transmitter and electrodes.

Vertical Jump measurement:

A Vertec jumping apparatus will be used to assess whether fatigue has taken place after the exercise protocol. The Vertec is often used to determine anaerobic power through vertical jump height. A small squat immediately prior to launch is essential for increasing power and vertical jump height through the stretch-shortening cycle. [65, 66]The squat stretches the quadriceps muscle group increasing the number of cross bridges. The increased number of cross bridges allows for greater force output upon the onset of shortening/contraction of the muscles. [65, 66] The Vertec is used as a functional assessment for force output due to the ease of testing and relatively low risk to the participant. Most college-aged populations are able to perform a vertical jump, which allows for comparison across populations. Fatigue will be determined to have adequately occurred if the participants' vertical jump measurement decreases by at least 50 percent when compared to pre-exercise protocol values.

Figure 3.6. Vertec Jumping Apparatus

Design and Procedures

The participants will arrive to the Blatt Physical Education Center for two separate days of testing. Day 1 will serve as a preparation day where participants fill out the health-screening questionnaire and measurements for electrode placement will be performed. If participants have no contraindications for exercise, then participants will perform 3 depth jumps to familiarize themselves with the proper mechanics. The testing session will occur on day 2 and will last approximately 90 minutes from participant preparation to the conclusion of data collection. Each participant will give written consent for the study, conditionally assuming approval by the Institutional Review Board of the University of South Carolina. The health-screening questionnaire will be used to eliminate participants who had any type of lower extremity injuries, which would prevent them from performing the game simulation protocol. The questionnaire will also screen for any allergy to adhesives, which will be used to collect electromyography data and attach the reflective markers.

Preparation of the skin of the participant and electrode placement will follow the recommendations of the surface electromyography for the non-invasive assessment of muscles. [49] The electrodes will be placed parallel with the muscle fibers of the muscle belly. The skin will be abraded and cleaned with an alcohol solution. The electrodes will be placed with a separation of 2 cm to ensure there is no interference between electrodes. Once the electrodes are placed on the participant, 7 reflective markers will be attached to the participant with double sided tape. The participants will be recommended to wear spandex shirts and shorts to ensure limited marker movement during data collection. Once the electrodes are correctly placed, a 5-second maximum volitional isometric contraction (MVIC) will be collected in order to normalize the measurements for the 6 muscles. [60, 61] The LD MVIC will occur with the participant in a prone position with extension and internal rotation of the shoulder. Pressure will be applied against the forearm in the direction of abduction and slight flexion of the arm. The GA MVIC will occur with the participant standing on two feet and performing bilateral plantarflexion of the ankle. Pressure will be applied against the shoulders bilaterally in the direction of dorsiflexion. The BF MVIC will occur the with participant lying prone and proceeding to flex the knee between 50 and 70 degrees with the thigh in slight lateral rotation and the leg in slight lateral rotation. The pressure will be exerted on the leg proximal to the ankle in the direction of knee extension. The RF and VMO MVICs will occur with the participant sitting with the knees over the side of the table and holding on to the table. The tests will consist of extension of the knee joint without rotation of the thigh and pressure will be applied against the leg above the ankle in the direction of knee flexion. The GM MVIC will occur with the participant lying on their side and the underneath leg flexed at the knee and hip, and pelvis rotated slightly forward. The hip will be abducted with slight extension and slight external rotation. Pressure will be applied against the leg close to the ankle in the direction of adducting and slight flexion. [60] Once the participant feels adequately prepared for the tasks, data collection will begin. Data will be presented as percent MVIC as a normative measure. Static position will be collected for all joint kinematics as a baseline.

An intermittent exercise protocol that has already been proven to induce the desirable levels of fatigue was chosen for this study. [34] Participants will perform various periods of walking, jogging, cruising, and sprinting. The treadmill speeds for each segment are based on typical speeds seen during sporting events such as soccer and lacrosse. The speeds chosen are as follows: walking 2.6 mph, jogging 5.5 mph, cruising 7.0 mph, and sprinting 9.0 mph. The protocol consists of two 22.5-minute periods with a recovery period of 10 minutes. During the 10-minute recovery period the participants will perform 3 depth jumps from the 18-inch box. This data will serve to prove fatigue has taken place due to the first half of the exercise protocol. If fatigue is seen, then this will serve as rationale for future research about ACL injury at an earlier period of time.

The total duration of the test representing approximately one full women's lacrosse game will be 50 minutes. Each 22.5-min cycle consisted of 23 discrete bouts of activity: Six bouts of walking, Six bouts of jogging, Three bouts of cruising and Eight sprinting bouts. The order of these bouts was designed to replicate the non-cyclical nature of the exercise pattern observed in lacrosse and soccer. High-intensity exercise (cruise and sprint) bouts were separated by low-intensity recovery (walk and jog) periods. The order of protocol with the low intensity recovery between each high-intensity bout will be randomized between the two low-intensity categories. The durations of the different bouts of activity were: walking 74.0 s, jogging 120.0 s, cruising 30.0 s and sprinting 12.0 s. The protocol was determined to be reliable and repeatable with a reported coefficient of variation of 4.8% and 95% ratio limits of agreement of 9.4%. [34] Fatigue was determined to have been attained if the participants' vertical jump height was less than 50% of the baseline jump height using the vertec jumping apparatus.

Assuming the fatigue guidelines have been met, the participants will perform five depth jumps. The depth jumps will be performed during the 5-minute recovery period (halftime) and immediately after the 2nd bout of the exercise protocol. sEMG data will be collected during all depth jump trials. Initiation of contraction will be considered the point closest to foot contact with the ground. The termination of contraction will be considered the last point at which the foot is remaining in contact with the ground.

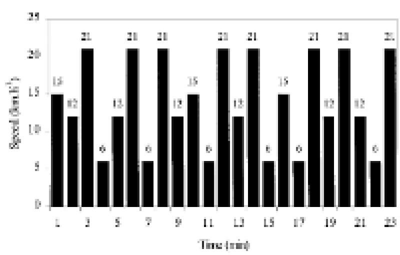

Figure 3.7. Example of a single half of game simulation protocol used by Drust et al. (2000).

Depth Jump

A depth jump is an exercise where the participant steps/leans forward until they jump off the front of the box. The individual will land on the ground with both feet simultaneously. The individual will bend their knees in order to assist in shock absorption upon landing on the ground. We will define the exact moment between the landing and jumping phase as the foot flat on the "ground" surface. Upon completing the landing phase, the participant will then begin positive acceleration and jump vertically. The transition from landing to propelling yourself into a vertical jump is a prime example of the stretch-shortening cycle. This stretch-shortening cycle is often studied when analyzing muscle force output in individuals. The mechanics of this movement can be seen in Figure 3.8.

Jumping and landing are common movements found in athletic events. This movement puts stress on the knee if the muscles are unable to assist in energy absorption. Hewett et al. (2005) demonstrated that females, with no history of ACL injury, landed with a similar knee flexion angle compared to females with a prior ACL injury. This data supports the reliability of using the depth jump for landing kinematic analysis in female athletes. For this study, the depth jump will be used to analyze knee kinematics during the landing and propulsion phases of a jump. By performing a depth jump we are able to avoid many of the "plant and twist" movements, which have been linked to increased risk of ACL injury. [4, 46, 52] By using a depth jump from an 18-inch box we are able to reduce some of the risk to the participants while still collecting the desired data. This is beneficial due to the fact that we will be able to analyze knee valgus and varus that is present during the landing phase. One common trend throughout most of the literature was the higher prevalence of ACL injuries during negative acceleration phases of movements. [4, 46, 52] Some factors, specifically foot pronation, will not be able to be analyzed through video due to the presence of shoes on the participants' feet. The majority of literature has focused on analyzing participants during cutting maneuvers. Cutting movements have been reported as a period of high stress on the knee, especially under fatigued conditions, which would put the participant at great risk. [12, 78, 113, 114, 122] Specifically, side-step cutting has been proven to elicit lower knee flexion angles, higher knee valgus angles and internal rotation angles at initial and maximum contact points. [25, 26, 91, 94] All three of these factors have been linked as factors for increased risk of ACL injury. The knee abduction moment has been found to be 6 times higher in sidestep cutting movements compared with two legged drop jump tasks. [67] Another strength of using a drop-jump task is the ability to standardize the task for all participants. The participants will have varying levels of knee flexion upon landing, but other than that the details will be the same.

Figure 3.8. Proper mechanics of a Depth Jump.

Statistical Data Analysis

All statistical analysis will be conducted using SPSS software and an alpha level will be set at, $p \leq 0.05$. Data will be imported to SPSS for analysis once sEMG rectification and smoothing is completed. To investigate the effects of fatigue on joint kinematics, sEMG activation order and sEMG before and after the fatigue protocol, 2-way ANOVA with repeated measures on both factors will be incorporated. A post hoc analysis and pairwise comparison will be performed for each dependent variable that resulted in statistical significance. Pairwise comparisons will be completed for any significant main effects between the independent variables with a bon-ferroni adjustment.

sEMG Analysis

The Noraxon sEMG data analysis software was used for all sEMG analysis. A root means square was used to determine the integrated sEMG signal for all trials. The initiation and termination of contraction will be compared between muscles at the same point in time. If a difference occurs between initiation and termination, then the area under the curve will be used to quantify sEMG activity of the contraction.

Video Analysis

Dartfish (Team Pro Version 7) will be used for all video analysis. This will be used to calculate the Q angle (knee valgus/adduction) and any lateral movement of the knee in the frontal plane. All angular data will be compared within individuals pre and post exercise protocol.

RESULTS

Table 3.2: Subject Demographics

n	10
Gender	Female
Age (years)	22.5 ± 3.09
Height (cm)	169.67 ± 5.33
Weight (kg)	67.45 ± 5.04

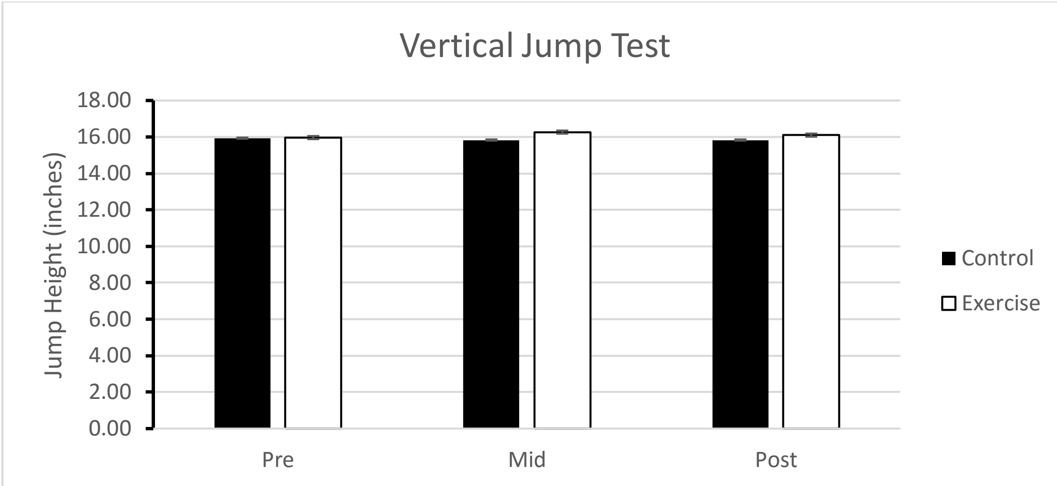

Figure 3.9: Vertical jump height was assessed pre, mid, and immediately post each session in both exercise and control conditions. The test was used as an index of fatigue. No differences were observed for vertical jump height.

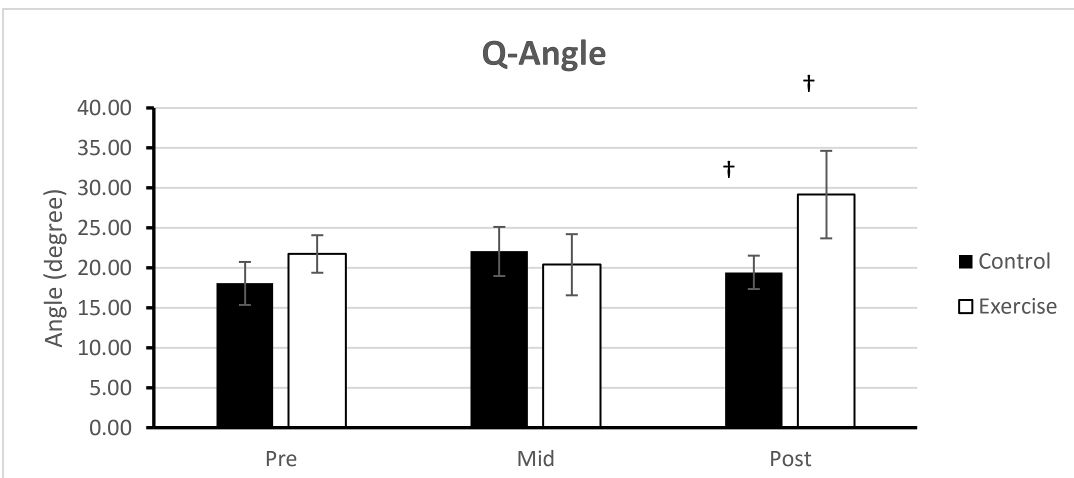

Figure 3.10: Q-Angle was assessed from 2-D video analysis of the landing phase from a box jump. The values from the Q-angle involving the knee and hip joints can be seen for pre, mid, and post measurements during the control and exercise sessions. Q-angle showed trend towards significance for the interaction between treatment and time.

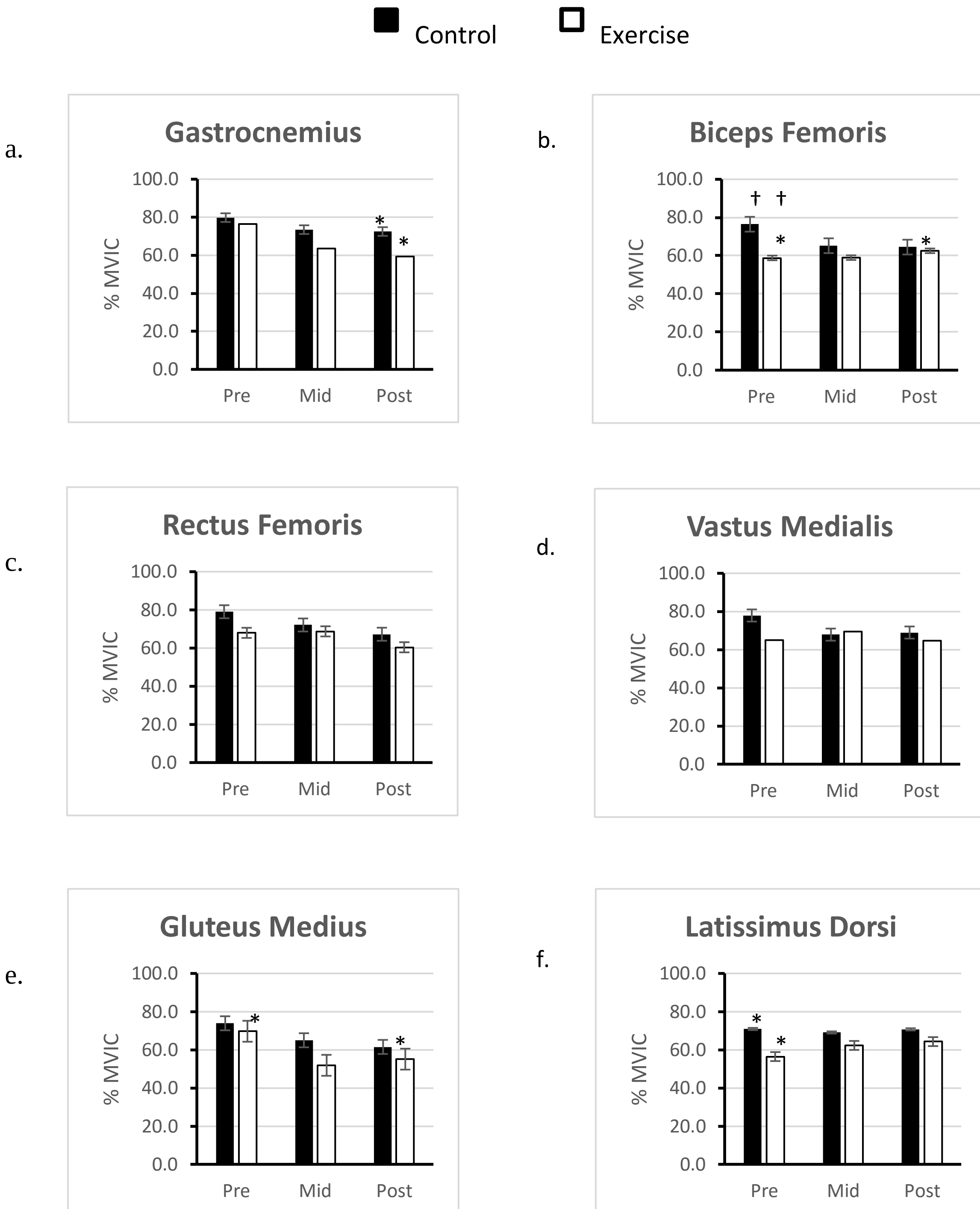

Figure 3.11: Percent MVIC values for select muscles during a landing task were measured pre, mid, and post sessions of exercise and control conditions. The BF indicated significance, while the GM, LD, and GA all trended towards significance.

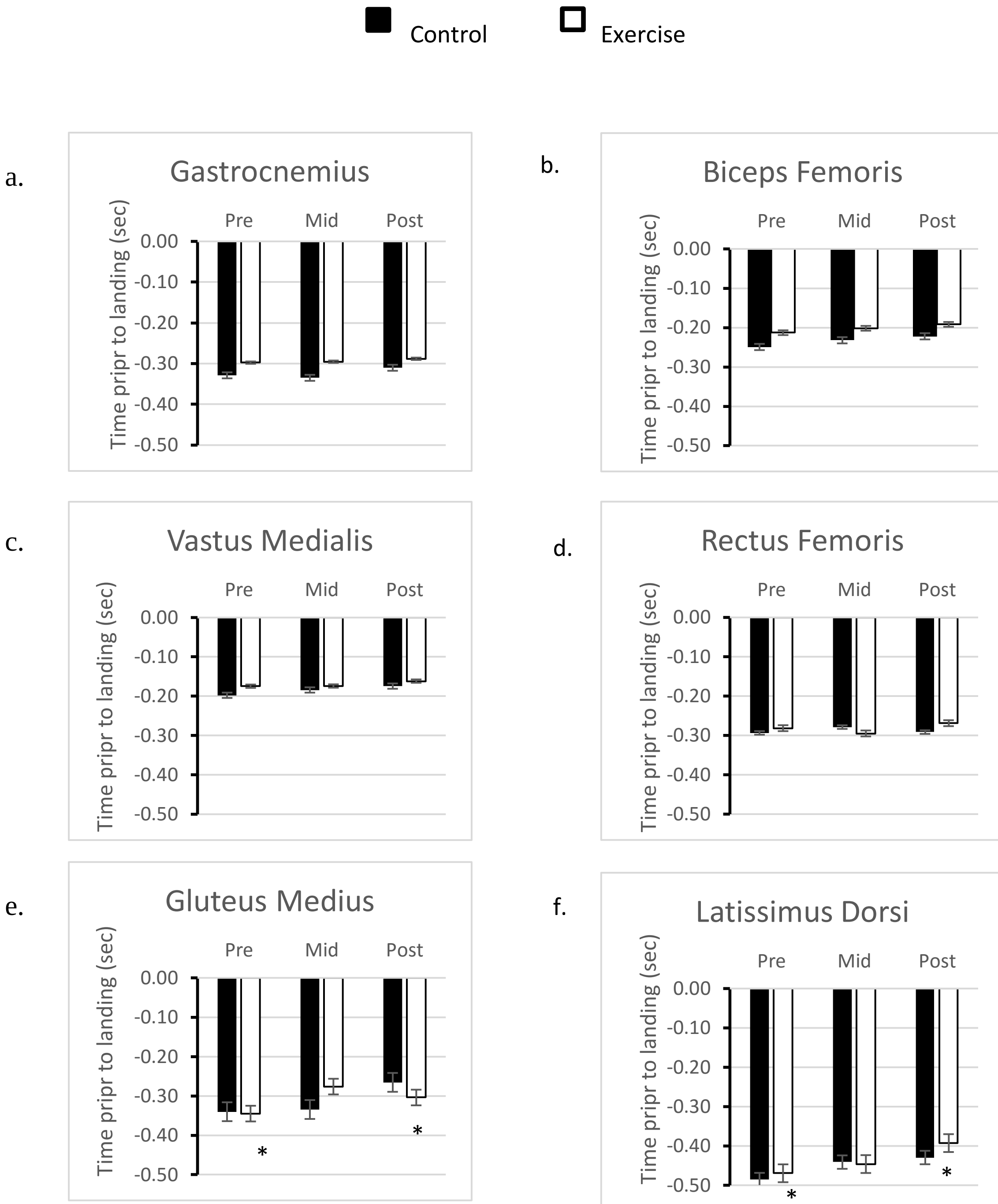

Figure 3.12: The timing of activation for the observed muscles is measured prior to the body reaching the point of zero acceleration for the control and exercise sessions. The LD muscle reached significance, while the GM muscle was trending towards significan

The participants for this study consisted of 10 physically active females that varied in age between 18 and 28 years old. Study participants completed sets of three box jumps and three vertical jump tests before (Pre), at half time (Mid) and immediately following (Post) the intervention. The vertical jump test assesses maximal jump height, however, reductions in maximal jump height support an increase in fatigue. The game simulation exercise protocol did not affect maximal vertical jump heights pre to post exercise, and there were no differences in maximal vertical jump height between control and exercise sessions as seen in Figure 3.9.

The Q-angle was measured for each participant when they reached the point of zero acceleration after jumping from the box. The Q-angle was determined by drawing one straight line from the Anterior Superior Iliac Spine to the center of the patella. A second straight line was drawn from the tibial tuberosity through the center of the patella. These two lines intersect and the resulting angle is the Q-angle. The statistics indicate a trend in the data for an increase in Q-angle when including both treatment and time with a p-value of 0.09, as seen in Figure 3.10.

The magnitude of muscle activation was recorded during the landing phase of the jumps. Figure 3.11 presents the magnitude, as a percentage of the MVIC for each muscle, during the landing phase after jumping from the box. The biceps femoris muscle achieved significance with a p-value of 0.041 between control and exercise as seen in Figure 3.11, graph b. The biceps femoris also resulted in significance with a p-value of 0.033 when analyzing the effect over time from pre to post. The gluteus medius muscles was found to have a trend towards significance with a p-value of 0.029 when comparing pre to post as seen in Figure 3.11, graph e. The latissimus dorsi muscle resulted in a trend towards significance with a p-value of 0.087 when comparing the control to the exercise sessions as seen in Figure 3.11, graph f. Analysis for the gastrocnemius muscle indicated a trend in the data with a p-value of 0.072 as seen in Figure 3.11, graph a.

The landing phase began at the point where neither foot remained in contact with the box and concluded at the exact moment when the participant reached an acceleration of zero. The timing of activation was obtained for each muscle once the participant was no longer in contact with the box. A timing value of -0.35 sec means that the muscle was initially activated 0.35 seconds prior to the participant reaching zero acceleration. The gluteus medius muscle was found to have significance with a p-value of 0.033 when comparing pre to post as seen in Figure 3.12 graph e. The gluteus medius muscle also resulted in a trend with a p-value of 0.093 when looking at the relationship between timing and control/exercise sessions. The latissimus dorsi muscle indicated significance with a p-value of .033 when comparing pre to post as seen in Figure 3.12 graph f.

DISCUSSION

The primary purpose of this study was to explore the effects of prolonged exercise sessions, simulating a game, on risk factors for non-contact ACL injuries. This study was designed in order to help coaches and players better understand the risk for ACL injury later in games. The results suggested that coaches may be able to avoid this increased risk by substituting their players more frequently to reduce fatigue and promote decreased risk for injury. Measurements were taken prior to either game simulation half (pre), in between the two game simulation halves (mid), and following the two game simulation halves (post). This is the first known study to show increased knee valgus following bouts of aerobic exercise without the presence of muscular fatigue.

Fatigue has been linked as a major risk factor for ACL rupture in female athletes in multiple studies. Previous studies stated fatigue negatively affected knee kinematics, magnitude of muscle activation, and forces on the ACL.[35, 41, 81] Some of these studies used changes in MVIC values as means for determining fatigue, which is a major limitation for those studies.[45, 106] A few of these studies used a vertical jump test to confirm the presence of fatigue.[59, 88] The exercise bouts in our study did not induce fatigue as assessed by the vertical jump test, yet we still observed decreases in BF and GM percent MVIC. This study focused primarily on exercise induced fatigue and could not differentiate whether this fatigue was central or peripheral. Exercise induced fatigue was expected to be defined as a decrease in muscle activation, any alteration in timing of muscle activation, or a change in knee kinematics. In this study, the vertical jump test was utilized to determine if fatigue was occurring throughout the experiment session. As seen in Figure 3.9, the data did not indicate any significant differences or trends when comparing across time (pre, mid, post) or across treatments groups. This suggests the game simulation protocol was not strenuous enough to elicit significant levels of fatigue in all participants. The exercise protocol used in this study was based on an exercise protocol used in prior studies.[34] The protocol for this study included slightly lower speeds on the treadmill compared to the original levels. The decision to lower the speeds was primarily based on the study population and a test trial of the exercise protocol. The original protocol was designed for male athletes of higher average fitness levels than our female population. Further research with an altered exercise protocol that is proven to induce fatigue is needed to confirm or reject these hypotheses. Previous studies found fatigue in the quadriceps, which would result in a decreased vertical jump height. [23, 87, 88, 93, 99, 100] The RF is one of the primary muscles for knee and hip extension which is required to maximize the vertical jump. Our study did not result in any changes in the RF activation, which may explain the lack of change in the vertical jump data. If the RF muscle activation was not decreased, then there would not be a lack of knee extension force to propel the body vertically. Despite the lack of exercise induced fatigue, significant changes related to muscle activation were observed during the landing phase of a jump.

The Q-angle of the knee is one of the greatest predictive risk factors for ACL rupture.[4, 21, 40, 103, 114] A higher Q-angle is often accompanied with an increased internal rotation of the femur. An increased level of femoral internal rotation will result in an increased knee valgus and greater stress on the ACL. [4, 80, 115] The BF and GM muscles are two primary muscles responsible for the prevention of femoral internal rotation. A decreased level of BF and/or GM activation would expose the individual to a less controlled internal rotation of the femur. Tsai et al. (2009) used a combination of sprinting and vertical jumps to induce fatigue within their participants. They reported increased knee internal rotation angle and knee adductor moment following their generalized muscular fatigue protocol. While they attribute these changes solely to fatigue, we found similar results without fatigue. As seen in Figure 3.10, during the exercise session, on average the Q-angle before the exercise exposure was 21.73 degrees and a post-exposure angle of 29.16 degrees. As seen in Figure 3.11, a significant decrease in the percent MVIC is seen for the BF muscle when comparing treatments and time independently. The decrease in biceps femoris activation supports the findings of Wojtys et al. (1996) who reported a decrease in both hamstring and quadriceps activation following fatiguing exercise. The current study also supports the findings of previous studies that a reduction in muscular activity will arise following increased duration of exercise. [4, 15, 23] The GM muscle indicated a trend towards a significant decrease in magnitude of activation over time as seen in Figure 3.11e. The GM muscle is primarily responsible for abduction of the hip when contracted. A decrease in muscle activation would not allow this primary function to occur effectively, thus resulting in greater hip adduction than normal.

Hip adduction is a known risk factor for ACL injury as determined by Sigward and Powers (2006). Sigward and Powers reported 80 percent of the females in their study demonstrated an adductor (valgus) movement during the landing phase of a jump. A combination of decreased BF and GM activation, potentially due to the exercise exposure, would expose the individual to a decreased ability to correctly control the negative acceleration during the landing phase of a jump. We report a decreased MVIC for the BF and GM muscles accompanied by an increased knee valgus moment, thus resulting in greater instability of the knee.

The GA displayed a greater rate of decrease in magnitude of activation during the exercise session compared to the control. The GA muscle is a secondary knee flexor that works in synergy with the BF muscle. As discussed previously, the BF muscle demonstrated a significant decrease in muscle activation. With a decreased BF activation, you would assume the GA has an increased activation to compensate for the lost control during the negative acceleration phase of landing. The data suggested a decreased GA muscle activation over time similar to the BF muscle. One possible explanation is the use of the GA for repeated concentric plantar flexion and eccentric dorsi-flexion during the game simulation exercise. The GA is a much smaller muscle than the BF, so could fatigue at a faster rate in the participants who are not endurance trained athletes. A decreased level of GA activation would further destabilize the knee. The combined effect of the reduced GM, GA, and BF muscle activation would allow for a greater knee valgus moment to occur at the knee. This increased knee valgus moment may lead to a greater Q-angle at the knee resulting in increased stress on the ACL itself, thus putting the individual at greater risk for injury. Another factor that places the ACL at great risk of rupture is the exposure to greater levels of anterior tibial translation.[81, 113, 128] This often occurs when the quadriceps muscles are activated at higher levels than the hamstring muscles. [99, 104, 122]

Zazulak et al. (2005) reported greater RF muscle activation in female athletes during the pre-contact phase of a landing task. An increase, or no change, in quadriceps activation, combined with lower hamstring activation, may contribute to a decrease in force absorption during landing. [134] This decreased absorption will result in an increased joint loading which has been reported to be associated with greater risk of ACL injury. [134] The RF and VMO did not display any significant changes in percent MVIC over time or when comparing control to exercise. If the RF and VMO muscle activation stays approximately the same while the BF is decreased, then the quadriceps to hamstring ratio will be greatly increased. Maintained levels of activation for the RF and VMO with a decreased BF activation would result in the anterior shift of the tibia. The BF muscle inserts on the styloid process of the fibula and the lateral tibial condyle. Under normal muscular activation the BF prevents the tibia from translating forward during periods of negative acceleration. Wojtys et al. (1996) determined this increased anterior tibial translation would exert extra force on the ACL, thus increasing the risk for ACL rupture. Thus, fatigue of muscles such as the BF, GM, RF, and VMO will result in greater instability and less control of the knee. Cutting and jumping motions in sporting events involve all four of those muscles to work together in order to correctly control the levels of negative acceleration in order to prevent injury.

The LD data demonstrated a trend in the data when comparing treatments, as seen in Figure 3.11f. The magnitude of the exercise values are lower in the exercise measurements than the control at all points in time. The exercise session resulted in a steady increase in percent MVIC from pre to post, while the control values stay fairly constant from pre to post. During rested conditions the hamstring and quadriceps muscles will be activated to assist in balance and body control during the landing phase. We reported a decrease in BF activation, so the LD was required to compensate for this lost force in order to maintain balance and body positioning during the landing phase of a jump. This opens the possibility of the LD and GM muscle having to contract at greater levels if the hamstring and quadriceps muscles are fatigued.

If the timing of muscle activation were altered, then the kinematics of the body during motion could expose the individual to a greater risk for injury.[22] If the hamstring muscles have a delayed activation while the quadriceps are activated on time, then the individual may be introduced to an increased anterior tibial translation. An increase in anterior tibial translation has been determined to be a major risk factor for injury.[81, 113, 128] The gluteus medius demonstrated a trend towards later activation during the pre and post measurements of the exercise session compared to the control values. This finding suggests that the GM was forced to activate later, which may be due to fatigue or the idea of the learning curve. Our findings of delayed activation are similar to those found by Huston and Wojtys (1996). Huston and Wojtys (1996) reported a slower response of hamstring activation to anterior stress on the ACL in female athletes under control conditions. If this is the case, then the tibia in females can shift further before contraction of the hamstring muscle occurs compared to males. Our data did not result in any changes in the order of activation due to fatigue, which is consistent with the findings of Wojtys et al (1996). Since the timing of activation didn't result in any significant changes, then the magnitude of activation is likely the cause for any changes in knee kinematics over time.

One possible explanation for the results is the participants adjusting and learning how to safely perform the task, while attempting to conserve a greater amount of energy. The timing of muscle activation was delayed for the GM and LD muscles. The question becomes, is this delay in activation due to fatigue or from the participants' familiarity with the task and knowledge of the last moment they can activate the muscle to conserve energy? The vertical jump data does not indicate significant fatigue occurring, which suggests the possibility of the participants becoming familiar with the activity and predicting when muscle activation is needed.[40, 42] Further research is needed with a multitude of trials and a more comprehensive EMG analysis to better understand the exact causes.

Conclusion

It was anticipated that significant changes in knee kinematics would be present only if fatigue was present following the exercise protocol.[4, 21, 35, 45, 80, 106, 118, 122, 128, 135] This was the first known study to find an increase in knee valgus without the presence of fatigue. The decrease in BF and GM activation allowed for a greater Q-angle to be formed at the knee. An increased Q angle will promote increased stress on the knee joint. This increased Q-angle and the resultant increase in stress on the knee are major known risk factors for ACL rupture as discussed in the literature review above.

Future directions

While this study elicited a significant decrease in biceps femoris activity with exercise, there are many limitations to the study. This study consisted of 10 participants, so a practical way to improve the power of this study is to attain the suggested sample size. If we were able to obtain 18 participants, the suggested number based on the power calculation, then we would see more accurate results that may be similar to the current findings. A second concern from this study was the lack of visual fatigue observed in the participants and from the vertical jump test results. Six of the ten participants were short of breath and sweating heavily following each of the exercise protocols. The remaining four participants had very few signs of fatigue and admitted to being regular long-distance endurance runners (2 run marathons and 2 run 5/10 kilometer races regularly). The inclusion and exclusion criteria needs to be more defined in order to obtain a more consistent desired population for the study. If the desired population is the endurance trained individuals, then the fatigue protocol itself should be altered. The ratio of periods can be altered to increase the number of cruise sessions and the duration of the sprint periods. The duration of the jogging phases would need to be shortened in order to accommodate these changes. Implementing a subjective measure for fatigue, such as the Rating of Perceived Exertion (RPE) scale, would strengthen the case for whether fatigue legitimately occurred. If the University of South Carolina Club Lacrosse or Soccer teams are willing, then a future study could be performed on them before and after a regular season game to compares changes from lab testing to live game testing.

The Q-angle data was the only information related to knee kinematics that was analyzed in this study due to the single camera view of the frontal plane. By using a 3-D video analysis system a better understanding of knee kinematics and changes due to fatigue can be seen. Any anterior shift of the tibia, a known risk factor for ACL injury, could be determined and analyzed throughout the study. If the participants in our study rotated their bodies prior to landing, then the knee angles were not accurate. The 3-D video analysis system would give a more accurate analysis for correct Q-angle measurements across all participants and all trials.

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