2012

Effect of Frontal Plane Foot Position on Lower Extremity Muscle Activation and Limb Positioning in a Single Leg Squat

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EFFECT OF FRONTAL PLANE FOOT POSITION ON LOWER EXTREMITY MUSCLE ACTIVATION AND LIMB POSITIONING IN A SINGLE LEG SQUAT

by

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A Scholarly Project Submitted to the Graduate Faculty of the

Department of Physical Therapy

School of Medicine and Health Sciences

University of North Dakota

in partial fulfillment of the requirementsfor the degree of

Doctor of Physical Therapy

Grand Forks, ND
May
2012

This Scholarly Project, submitted by Elizabeth J. Kornkven in partial fulfillment of the Requirements for the Degree of Doctor of Physical Therapy from the University of North Dakota, has been read by the Advisor and Chairperson of Physical Therapy under whom the work has been done and is hereby approved.

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(Graduate School Advisor)

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Department	Physical Therapy
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ABSTRACT

Purpose/Background: Foot positioning during a single leg landing may affect the muscles above the ankle joint and promote positions of increased vulnerability to ACL injury. The purpose of the study was to analyze muscle activity of six muscles in the lower extremity during completion of a single leg squat on the subject's dominant leg with the subtalar joint in 5 different positions.

Methods: Seventeen healthy males and females (ages 18-30) performed five single leg squats in five foot positions: neutral, five degrees and ten degrees of declination, and five degrees and ten degrees of inclination. Electromyography data was collected from electrodes placed over each muscle. The declination mimicked pronation while the inclination mimicked supination of the foot/subtalar joint.

Results: The ten degree angle of pronation had the highest % MVC in four of the six muscles including anterior tibialis, lateral gastrocnemius, gluteus maximus and gluteus medius. With the high variability and large standard deviations, we are unable to make certain of our results. On average, the gluteus maximus muscle had the highest % MVC for all foot positions while the anterior tibialis had the lowest % MVC at 60.22. Lateral

gastrocnemius, biceps femoris and gluteus maximus were the three muscles showing statistically significance using Friendman's. Friedman's was chosen as our study violated assumptions which prevented us from running a parametric test.

Conclusions: Pronation caused the highest % MVC which makes us suspect that the distal joint of the ankle can impact the degree of muscle activation above that joint. This also could be a position of vulnerability as it causes the muscles to contract more which could be secondary to instability, malalignment, or some other factor. More research is needed to study the effect of pronation as our study had several limitations.

CHAPTER I

INTRODUCTION

The purpose of our study was to determine whether different foot positions altered muscle activity of the lower extremity during a single leg squat (SLS). Our study explored the influence of foot positioning on lower extremity muscle activity and what positions may place the knee joint susceptible to injury. Research has indicated overpronation of the subtalar joint may place the anterior cruciate ligament (ACL) at increased risk of injury.[1] Electromyogram (EMG) data was collected for six different muscles on five different inclines, including pronation, supination, and neutral. ACL injuries tend to occur when the knee joint is extended, in valgus alignment, and in tibial internal rotation.[2] Our research question was whether the foot positioning would have an effect on the above stated positions and result in a change of muscle activation.

Several factors are under study to assess the cause of altered movement patterns and vulnerable knee positions which place the ACL at increased risk of injury. These factors include environmental (shoes, playing surfaces), biomechanical, neuromuscular, anatomical, and hormonal factors, with current research focusing more on the areas of neuromuscular and biomechanical factors because of their modifiability.[3,4] Intrinsic and extrinsic factors are also under study. Intrinsic factors are more gender specific and include joint laxity, limb alignment, intercondylar notch size and shape, ligament size and strength, hormonal levels, and foot abnormalities as well as age and maturation.[5] Some of these factors may be the reason for the gender difference; however, some males may exhibit similar characteristics as females do and place them at increased risk as well.[6] Physical maturation impacts all of these risk factors. An athlete's past family history is important since several risk factors have a genetic link.[9] Extrinsic factors include conditioning levels, body movement and positioning, muscular strength and neuromuscular coordination/performance, and shoe wear/shoe surface interface. Overuse from performing the same activity for long periods of time is a concern for athletes as well and may result in ACL injury. Even as these risk factors have been identified and increased research has been done on the prevalence of ACL tears, the rate of injury remains stable,[10] signifying an area for continued research. Included is an analysis of the current literature and a comparison to our research results to better understand why ACL injuries occur.

CHAPTER II

REVIEW OF THE LITERATURE

The anterior cruciate ligament is known for its susceptibility to injury during vigorous athletic activities. Extensive research is being done as to the cause of ACL injuries and why females are 2 to 10 times more likely to suffer from ACL tears than males.[1,10,11] A majority of ACL tears are noncontact (70%)[11,13] and occur when a sudden compression force is placed on the knee in combination with increased valgus and internal tibial rotation moments.[14] These injuries usually occur in athletes and physically active individuals. A large percentage of sports injuries are knee injuries[15] and these injuries have short term as well as the potential for long-term consequences which may include an earlier onset of degenerative osteoarthritic changes.[16,17,18] These injuries also can have a psychosocial impact on a person's well-being and may affect his/her lifestyle.[19] ACL ruptures can be costly and when treated with surgery and rehabilitation can cost around $17,000 to $25,000 per injury not including the amount lost in scholarship funding, sports participation, long term disability, and osteoarthritis.[12]

Several research studies are being conducted to identify why ACL tears occur more often in females. Recent evidence has pointed to a gender difference in neuromuscular response (of lower extremity muscle groups) during lower extremity landing positions as a likely cause. Females tend to land with more knee extension and with a more valgus alignment ("knocked knee" position), which causes increased anterior tibial translation, placing increased strain on the ACL. Females may be more at risk due to anatomical, hormonal, and neuromuscular factors. The ACL provides 86% of the resistance to anterior tibial translation, so when excess force stresses the knee, the muscles around the knee must contract effectively in order to enhance joint stability.[20,21,22] Posterior kinetic chain muscles, which are especially important for lower extremity control, include the gluteals, hamstrings, gastrocnemius, and soleus. By cocontracting the quadriceps and hamstrings during jump landings, pivoting, cutting, and other maneuvers, the individual can reduce the amount of loading on the ACL, decreasing injury potential. This cocontraction can be trained by neuromuscular programs and is critical in protecting the ACL.[21] Research appears to focus mainly on seven different areas of lower extremity alignment including pelvic angle, hip anteversion, Q-angle, genu recurvatum, tibial torsion, navicular drop (foot pronation), and rearfoot angle. Many researchers have looked at the causes of ACL injury from a top down approach, meaning poor control at the more proximal joints can position the more distal joints/ligaments/muscles of the lower extremity in a vulnerable position for ACL injury. This hypothesis has merit but research also supports malpositioning of the foot as a promoter of ACL tears, which is a bottom-up approach. Understanding these risk factors and knowing which ones are significant and modifiable will allow prevention efforts and training programs to be instituted to lower the prevalence of ACL tears, especially in females.

Females have excess variability in their movement patterns, a characteristic which could be detrimental. Biomechanical factors which differ in females include increased knee valgus angles, decreased hip flexion angles, and increased knee extension during dynamic movements. All of these can be influenced by alignment.[6] Females are more likely to have nutritional issues which include a diet low in calcium or carbohydrates or they have disordered eating habits so their body is not adequately nourished to withstand the stress of activity and therefore more at risk for injury.[23,24,25] Another issue with high school females is sleep deprivation; not getting enough sleep impacts fatigue level, alertness, and overall performance.[26,27,28,29] Females are also impacted more by stress which can cause depression and anxiety; depression and low self-esteem have been linked to sports trauma.[30] Females also generate less torque overall in all muscle groups.[31]

Current research points to females as being the highest risk athletes, especially those who play basketball or soccer.[11] Several risk factors have been identified but research conflicts as to the contribution of each factor. Certain factors receive more attention than others, but it is clear the entire kinetic chain (from trunk to foot) should be examined since ACL tears appear to be multifactorial. Foot alignment has been found to possibly correlate with hip joint dysfunction and increased stress at the knee joint.[35] Asymmetry, from side to side, should be looked at in athletes, as imbalances in muscle size, length, and recruitment can increase the risk of injury. Several studies show proximal tibial anterior shear force, valgus/varus moment, and internal/external rotation moments as three possible ACL loading mechanisms. In vivo studies show that ACL loading decreases as knee flexion angle increases, and they also suggest that proximal tibia anterior shear force stresses the ACL the most.

Seven key variables were looked at in one study (and seem to be the focus of most research on ACL tears) to assess the correlation between static postural faults and the number of noncontact ACL injury in females.[33] The seven variables included standing pelvic position, hip position, standing sagittal knee position, standing frontal knee position, hamstring length, prone subtalar joint position, and navicular drop test. Three of these were significant when comparing ACL injured females to age-matched healthy individuals: knee recurvatum, excess navicular drop, and excess subtalar joint pronation.[33] Abnormal lower extremity biomechanical control mechanisms are related to knee pathologies. Females have different static postural faults than males, impacting dynamic movements and increasing ACL stress. These differences include anterior pelvic tilt, anteverted hips (increased internal femoral rotation), tight hamstrings, genu recurvatum, and subtalar joint pronation, all of which can cause increased knee hyperextension and internal tibial rotation (shown to be vulnerable positions for the ACL).[1] During dynamic movements, female athletes have greater navicular drop, larger Q-angles, weaker hamstring strength, and stronger quadriceps contraction (relative to hamstring contraction) than males.[33]

Three female-specific risk factors include (1) the preovulatory phase of the menstrual cycle, (2) decreased intercondylar notch width on plain radiography, and (3) increased knee abduction moment during jump landings.[4] The anterior intercondylar notch height is higher and the notch angle is smaller in females.[4] Norwood and Cross[33] found the anterior intercondylar notch impinges the ACL during full knee extension. Females land in more knee extension which would tend to impinge the ACL more than when males land in more knee flexion which would cause less damage.

Females use different cutting, landing, and single leg squatting techniques than males do. During dynamic movements, a female's knee tends to move into a valgus alignment while males tend to move into a more neutral alignment. Postural stability during dynamic movements is influenced by the strength of the hip abductors, external rotators, quadratus lumborum, abdominal muscles, and back extensors. Females tend to lack control which may play a role in the gender bias.[35,36] Females are more likely to have hyperlaxity especially at the knee joint. They tend to have more than 10 degrees of knee hyperextension (genu recurvatum) which is a risk factor for overuse injuries. Ligament remodeling can play a role in the gender disparity as male and female hormones/genes are expressed differently and female ACLs usually have a smaller cross sectional area.

Neuromuscular control may be influenced by estrogen receptors in the skeletal muscle. Estrogen levels can change throughout the menstrual cycle and appear to be elevated during the ovulation phase. Estrogen affects how women respond to demands of exercise and competition.[37] Higher levels of estrogen increase connective tissue extensibility and decrease neuromuscular control. Women utilized a different neuromuscular control pattern during a drop jump sequence when their estrogen levels were high versus when they were low (luteal vs early follicular phases, respectively).[38] Estrogen seems to affect foot dynamics the most; increase in endogenous estrogen level may increase ligament extensibility and result in a more pronated position of the talocalcaneonavicular and transverse tarsal joints, both statically and dynamically. During ovulation, females may have a loss of postural control which can shift their center of mass (COM) and thus affect their foot center of pressure.[39]

Maturation can have an important consequence on risk of ACL injury. During puberty, females show a significant increase in their angle of knee abduction, whereas males show no change. These knee abduction moments are greatest immediately after a growth spurt.[40,41,42] More than half of all ACL injuries occur between the ages of 15 and 25, possibly due to maturation and timing of gender differentiation.[43] Females have musculoskeletal growth during puberty but lack corresponding neuromuscular adaptations, a deficiency which can develop into intrinsic ACL injury risk factors.[40,44]

Knee valgus is a position of increased stress on the knee joint. Knee valgus has several component motions including femoral internal rotation and adduction, tibial abduction, and ankle pronation (eversion).[2,45] Females are mainly quadriceps dominant and when their quadriceps contract more than their hamstrings or gluteals do, the knee goes into a position of valgus collapse.[47] Maximum knee valgus occurs during the first 50 ms of initial contact, which would be during initial muscle contraction.

Subtalar pronation is another risk factor assessed in research studies. The ACL becomes taut with coupling motions of pronation in the frontal plane and internal tibial rotation in the transverse plane.[33] Pronation and internal rotation increase anterior joint laxity, which allows for maximal anterior tibial translation and increases stress on the ACL.[46] Research looking at the relationship between subtalar joint alignment and ACL tears has mixed results. Foot pronation is measured by navicular drop and calcaneal stance and can be caused by a varus forefoot alignment.[47] Navicular drop is the distance the navicular tuberosity travels while standing when the subtalar joint moves from a neutral to a relaxed position.[1] Studies have found excess subtalar joint pronation to contribute to ACL injury[49] while other studies found hyperpronation did not predict ACL injury and would not be a contributing factor.[47] Males and females may show similar foot structure which means even if pronation is a factor, it may not be a cause of the gender disparity.[11] When comparing ACL injured to non-injured individuals, ACL injured individuals have greater navicular drop test scores.[33]

Anterior tibial translation (ATT) occurs when the quadriceps contract more than the hamstrings.[50] ATT can be limited by increasing medial hamstring activity during initial contact. ACL rupture can occur with excess tibiofemoral compression which occurs during axial tibial loading as an anterior tibial shear force is placed on the proximal lateral tibial plateau. Anterior shift may be more likely to occur in individuals with an increased posterior tibial slope (PTS) due to its effects on knee kinematics and kinetics.[51,52,53] Sagittal plane trunk position during landing can affect the amount of ATT that occurs at the knee. Landing with a vertical trunk causes the greatest amount of tibial shear and greater ground reaction forces compared to landing with a forward lean. Increasing trunk control may decrease the amount of anterior tibial translation (also called sagittal plane shear stiffness) and thus decrease the amount of ACL tension.[54]

ACL injuries are most likely to occur while the individual (either gender) is landing from a jump (and usually while on one leg) so it is important to know the positions which increase the likelihood of a tear and should be altered by training. Dynamic movement patterns must be coordinated with proper proximal muscle firing patterns in order to prepare for a safe landing. A gender discrepancy exists at the proximal and distal joints during dynamic movements. A few of the specific vulnerable positions found in females during jump landings will be discussed. These positions usually include increased knee extension, valgus alignment, and ankle pronation, all of which cause a wider landing stance.[1] Landing with a flat foot (pronation) may reduce the ability of the calf muscles to dampen the ground reaction forces before they reach the knee.[56] Females tend to lean laterally which shifts their center of mass outside their base of support thus increasing forces at the knee joint.[57] Males usually land asymmetrically with toes-out and heel contact first. A univariate analysis demonstrated low BMI, increased Q-angle, and poor gluteus medius strength can predict poor landing technique in males. Only lower BMI and weak hip internal rotation strength significantly contributed during this analysis. This suggests even if an athlete's alignment, BMI, or muscle strength is changed, it may not directly improve his or her movement patterns.[57]

Five groups of errors may identify patterns which cause poor body alignment/muscle activation, these include: 1) decreased sagittal trunk, hip and knee flexion at initial ground contact; 2) valgus knee and wide stance at initial contact; 3) toes out and knees flexed at initial contact; 4) heel strike landing and asymmetric foot strike landing; 5) less sagittal flexion over the landing phase. Females tend to land with an upright trunk, more hip and knee extension and more internal hip rotation, tibial rotation, and knee valgus than males.[58] Knee motion and knee loading during landing tasks can predict the likelihood of an ACL injury. Females should be screened for increased dynamic valgus and high abduction loads, as they could benefit from targeted interventions to decrease this risk.[44]

Impaired neuromuscular control may contribute to the increased frequency of noncontact ACL injuries especially when combined with lack of experience and poor neuromuscular mechanics.[33,57] Females have less neuromuscular control during dynamic landings than males. Lower extremity muscle premotor times were examined from stimulus presentation until initial muscle EMG activity in order to determine if a difference existed on knee abduction loads during anticipated and unanticipated single leg landings for the dominant and nondominant foot. Peak knee abduction and internal rotation moments were significantly larger during unanticipated compared to anticipated landings (twice as high)[40] and were correlated with medial gastrocnemius and medial hamstring premotor times. These findings were significant for both legs. The medial hamstring and medial gastrocnemius were proven to be critical in stabilizing the knee against extreme dynamic load stresses. It may be important to strengthen these muscles and improve their ability to sense and prepare for unanticipated events.[59]

Females have altered muscle timing patterns and imbalanced quadriceps to hamstrings activation.[33,55] Weaker hamstrings and decreased hamstring/quadriceps (H/Q) strength combined with increased valgus knee motion is found in women.[5,60] A stronger quadriceps contraction with insufficient hamstrings cocontraction can cause decreased knee flexion during single leg landing. Sufficient cocontraction is beneficial as it decreases the load on the ACL by unloading the knee ligaments and increasing dynamic joint stability. Decreased hip muscle control may also be a cause for frontal plane knee movement.

Trunk control has received more focus lately to study how core strength and trunk movements affect lower extremity alignment. Greater lateral trunk positioning has been found more often in females than males. The neuromuscular system must respond when the COM goes outside an individual's base of support. A greater abduction angle correlates with a lateral trunk lean. When the trunk leans forward, a greater plantar flexor moment occurs and a minimal knee extensor moment occurs, which decreases quadriceps contraction and increases hamstring contraction, decreasing tension on the ACL. Trunk position and the body's response to this trunk movement can increase or decrease the risk of ACL injury.[55]

The hip joint and surrounding muscles may also influence knee vulnerability. One study[62] assessed gluteus medius strength and the relevance of hip abduction fatigue to ACL tears. This study found the lower extremity mechanisms below the hip can be altered by hip abduction fatigue due to the inability to maintain proper alignment, especially during drop jumps and cutting maneuvers. Women are routinely shown to have more knee valgus during a squat or jump landings which correlate with weak hip abductors. Weak hip abductors (especially gluteus medius) may predispose the person to land with hip adduction and internal rotation, which can increase knee abduction angles and result in anterior tibiofemoral shear forces. The effect of hip abduction fatigue is controversial since some studies found it did affect the likelihood of ACL tears[60] while other studies disagree. Along with core stability, athletes should have adequate strength of the hip abductors and rotators to control/stabilize the pelvis and maintain symmetry. The hip external rotators are a stabilizing component for the core and for the lower extremity.[64] Some studies concluded weak hip external rotator strength can predict injury status in female athletes.

When video sequence is done on the knee, four common motor performance components are found to occur. The four neuromuscular imbalances that occur during movement include ligament dominance, quadriceps dominance, leg dominance, and trunk dominance. Neuromuscular factors such as muscle timing and activation patterns (quadriceps, hamstrings, gastrocnemius) during anticipated and unanticipated tasks may be important.[4,63] *Ligament dominance* is dependence on the ligaments to absorb high amounts of force, since the muscles are not able to do so sufficiently. This places the ligaments at increased risk of rupture due to the inability to control lower extremity frontal plane motion. Females rely on ligament dominance because they have delayed muscular activation.[3] *Quadriceps dominance* is an imbalance between knee extensor and flexor strength, recruitment, and coordination which causes females to land with less knee flexion than males. Females activate their quadriceps first and rely on their quadriceps to stabilize, causing knee joint extension and pulling the tibia forward to increase ACL strain. Males activate their hamstrings first, pulling the tibia posteriorly to decrease ACL strain.[64] *Leg dominance* is an imbalance between the two lower extremities in strength, coordination, flexibility, and control. Females tend to favor one leg over the other. When a female tears her ACL, most of her weight is on one leg while males tend to have symmetrical strength, coordination, flexibility, and recruitment in their lower extremities and land on both legs.[64] Both legs may be at risk for injury since the weaker leg is compromised in its ability to handle the forces while the stronger limb may experience higher forces and require greater stability.[3] The last neuromuscular control deficit observed is *trunk dominance* which is an imbalance between inertial demands and the trunk control and coordination to resist those demands; females tend to have excess trunk motion. Athletes, typically women, have a difficult time sensing the position of their trunk in space, tend to have more trunk movement, which increases risk of injury. The ground reaction force (GRF) is directed toward the COM so it is important to control trunk motion so COM remains within the base of support. If the trunk moves laterally, the COM moves laterally as well and shifts over one knee, creating a valgus alignment on that side. By training trunk muscular control, lateral movement can be decreased.[64,65] A good way to assess female athletes for any of these neuromuscular flaws is having them complete a tuck jump and identifying whether any of these occur.

The frontal plane is used to study valgus alignment and is associated with anticipated lower extremity and trunk movements.[4] In order to have a thorough understanding of what happens in the frontal plane at the knee, we must also consider forefoot alignment (ankle eversion) and hip joint alignment (femoral internal rotation and adduction). It is very unlikely ACL injuries occur solely in one plane but rather in multiple planes (frontal, sagittal, and transverse), so muscles controlling movement in all planes deserve attention.[66]

One of the goals of ACL research is to identify specific risk factors at which prevention programs can be aimed to decrease the frequency of ACL injuries. No universally accepted ACL injury prevention program yet exists, but the program will likely need to be diverse and focus on all planes of movement since ACL injuries are multifactorial. These programs can be critical for individuals found to be at risk, especially female athletes, and may be most important when females are experiencing their growth spurts during adolescence.

Research has indicated that overpronation of the subtalar joint may place the ACL at risk for injury. We studied the influence of foot positioning on muscular control of the lower extremity and the possibility of creating at risk positions. We hypothesized foot positioning away from a more neutral subtalar position can promote ACL tears by altering muscle activity of the more proximal lower extremity joints, including the hip and knee. This approach would hypothesize the injury is caused from a bottom-up approach. The top-down approach hypothesizes that poor motor control at the more proximal joints, like the hip, positions the rest of the lower extremity (knee, ankle, foot) at a more vulnerable position for an ACL injury. We looked to see if a change in foot position does in fact change the muscle activity above that joint, thereby implying that the knee would assume greater forces when muscle activity changes.

CHAPTER III

MATERIALS AND METHODS

Subjects

Seventeen healthy subjects with no current leg injury volunteered to participate in our study. These subjects did not have to be physically active but did have to be between 18-30 years old (average age 23.7 years old, SD 1.947). Both males and females were included in the subject pool. The subjects had an average height of 169.55 cm (SD 8.298) and average weight of 67.7 kg (SD 14.060). All subjects were left leg dominant as described below except for one. Exclusion criteria included any acute lower extremity injuries or pregnancy.

Subject Preparation

Prior to the test, each subject completed a questionnaire listing prior injuries/surgeries in the lower extremities, date these occurred, and on which side of the body. They were also asked if they were pregnant and the day their most recent menstrual cycle began (if applicable). Other anthropometric data collected included height, weight, age, and various lower extremity segment lengths. Informed written consent was obtained from each participant prior to start of the study in accordance with the university's institutional review board. Subjects were required to wear shorts and remove their socks and shoes. We wanted the squat to be completed on the dominant lower extremity. To determine this, we rolled a ball toward the subject and instructed him/her to kick it. The dominant leg was the leg spontaneously chosen to stand on when the ball was kicked. We had the subjects kick the ball three times and chose the stance leg they used on the best of 3 trials (Shultz et al Sports Health 2009).

We used surface electrodes to measure the electrical activity for six different dominant leg muscles during the single leg squat. For each participant we measured and marked locations for surface electrodes to be placed on the dominant leg for each muscle using the landmarks described in Eleanor Criswell's book.[67] Electrodes for the muscles examined were positioned as follows: gluteus maximus - midpoint of a line running from the inferior lateral angle of the sacrum to the great trochanter; gluteus medius - proximal third of the distance from the iliac crest to the greater trochanter; biceps femoris - midpoint of a line from the ischial tuberosity to the lateral femoral condyle; rectus femoris - midpoint of a line from the ischial tuberosity to the lateral femoral condyle; gastrocnemius - one third of the distance from the fibular head to calcaneus; anterior tibialis - one third of the distance from the inferior patellar pole to the lateral malleolus; ground electrode – over the fibular head on the dominant leg. An electric goniometer was placed on the dominant lateral knee to measure the squatting angle. Thorough skin preparation was then completed to prepare the area for electrode placement. In order to minimize skin impedance, we removed any excess hair using an electric razor, abraded the skin gently with sand paper, and then wiped the area with rubbing alcohol. EMG electrodes were placed with one inch between their centers, making sure the markers did not touch each other, in order to pick up higher frequencies and reduce the amplitude of EMG signal. Once the EMG electrodes were in place, we checked each area with a Noraxon electrode impedance checker; impedance needed to be below 5 Kohms. If impedance was not below 5 kohms, electrode placement was adjusted and rechecked. Each participant had to contract each muscle individually to check if the electrodes were recording muscle activity correctly.

Experimental Design

The study used a repeated measures design examining the effect of five different foot inclines on muscle activation. Repeated measures design is more powerful because it reduces error by decreasing variability. Each participant completed the squat on all five inclines.

Data Collection

All research was conducted in the Physical Therapy Department located in the UND School of Medicine and Health Sciences building. EMG data was captured using "MyoResearch XP Master Edition" version 1.08.17. The developer is Noraxon USA. Inc, Scottsdale AZ. Comparisons of muscle activity among different foot positions were made to draw inferences regarding foot position influence on motor control in the lower extremity. The investigators and participants were not blinded to the purposes of this study.

We collected electromyography (EMG) data for six different lower extremity muscles during a single leg squat on five different inclines to analyze muscle activity changes. The six muscles included gluteus maximus, gluteus medius, quadriceps femoris, hamstrings, anterior tibialis, and gastrocnemius. Our five incline surfaces included five degrees declination, ten degrees declination, neutral, five degrees inclination, and ten degrees inclination. The declination mimicked pronation while the inclination mimicked supination of the foot/subtalar joint. Each participant was barefoot and instructed to stand on the middle of the wooden surface for all five positions (surface was covered with a towel). EMG activity was recorded during the lowering (eccentric) and the raising (concentric) phases of the single leg squat for five repetitions for each of the five foot positions. Participants had to complete the squat without holding onto anything for support. We used the EMG activity from the second, third, and fourth squats at each position and discarded the first and fifth squat data.

Neutral (standard) was the first foot position used for all subjects. EMG activity for each muscle was compared to an average maximal voluntary contraction for the specific muscle. The remaining order of inclines were determined by drawing from four cards. This random order helped control effects of fatigue as well as practice effects which could occur by the time they completed the fifth position. Subjects performed a few squats on the flat surface to check the connection between the electrodes and the computer program. All squats were performed in time with a metronome set at 60 Hz, with one squat cycle comprising 2 seconds each, with each subject descending on the tone and ascending on the subsequent tone.

MyoResearch XP Master Edition recorded the data for each muscle throughout the entire squat, with baseline recordings before and after the squat. Subject means were calculated for each muscle group during each of the five inclines. The average maximal voluntary capacity was used to compare all data to in order to normalize the results. The subjects were allowed to practice 4 to 5 squats before data was collected. The ideal goal was for each subject to squat to a 50 to 60 degree angle of knee flexion. The subjects had a rest interval of approximately 30 seconds between inclines. After the patient completed all foot positions, electrodes were removed, discarded, and the subject's skin was wiped with rubbing alcohol. Little risk is associated with our study and only moderate physical effort is needed. A loss of balance during the squat may be an issue but a spotter was present to assist if needed. Skin reactions could occur due to the electrode adhesive but would resolve spontaneously.

Statistical Analysis

A repeated measures ANOVA using a two way ANOVA design was utilized to test our hypothesis. The same subject completed the squats on each surface making it a repeated measure (within-subject independent variable) statistical design. Each muscle was analyzed separately across positions. At each position, a percent of the maximal voluntary contraction (% MVC) was found by comparing muscle activation to the average maximal voluntary contraction (MVC) value of participants in a preceding study. Alpha for all statistical tests was .05. EMG data for each muscle was compared across the 5 positions. Friedman's Test, a nonparametric repeated measures statistical test, was initially chosen to analyze our data due to our EMG data not being normally distributed. The post hoc comparisons of a repeated measures ANOVA determined significant EMG differences between positions. This was justified as decisions relative to the null hypotheses were identical for all muscle groups using the Friedman's Test and the RM ANOVA. The independent variables were foot positioning and the six muscles assessed. The dependent variable was the amount of muscle activity of each muscle at each foot position.

CHAPTER IV

RESULTS

Muscle activation of the lateral gastrocnemius, rectus femoris, biceps femoris, gluteus medius, gluteus maximus, and tibialis anterior was monitored and recorded during a single leg squat in 5 different foot positions. The mean and standard deviation for each foot position is listed in Tables 2.1 to 2.6 (p. 23-25). Results from Friedman's tests is listed in Table 1 (p.23), and the RM ANOVA tests are presented in Tables 3.1 to 3.6 (appendix). Pronation was found to cause significant changes in muscle activation above the ankle joint. This can impact the functional capacity of the lower extremity and may place the knee in a less than optimal position.

Tibialis Anterior, Rectus Femoris, and Gluteus Medius

Muscle activity of the tibialis anterior, rectus femoris, and gluteus medius was not statistically significant among foot positions according to Friedman's ($p=.692$), ($p=.263$), ($p=.193$) respectively. The change in foot position did not change the amount of muscle contraction for these muscles to a significant degree.

Lateral Gastrocnemius

Muscle activity of the lateral gastrocnemius was found to be statistically significant with changing foot position ($P=.014$; $p<.05$). According to the post hoc analysis there is a significant difference in lateral gastrocnemius muscle activity between the following positions: neutral foot position and 5 degrees pronation ($P=.050$); 5 degrees supination and 10 degrees pronation (*p*=.035); 10 degrees supination and 5 degrees pronation (*P*=.020); 10 degrees supination and 10 degrees pronation (*P*=.035). The change in foot position did affect the amount of muscle contraction for this muscle.

Biceps Femoris

Muscle activity of the biceps femoris was found to be statistically significant with changing foot position (*P*=.046) According to the post hoc analysis there is a significant difference in biceps femoris muscle activity between the following foot positions: neutral foot position and 5 degrees pronation (*P*=.010); neutral foot position and 10 degrees pronation (*p*=.008). During pronation is when the most muscle activity was fired in this muscle.

Gluteus Maximus

Muscle activity of the gluteus maximus was found to be statistically significant with changing foot position (*P*=.000). Follow up pairwise comparisons test showed there was significant difference in gluteus maximus muscle activity between means for the following foot positions: neutral foot position and 5 degrees supination (*P*=.021); neutral and 10 degrees supination (*P*=.023); neutral and 5 degrees pronation (*P*=.002); neutral and 10 degrees pronation (*P*=.001); 5 degrees supination and 10 degrees pronation (*P*=.003); 5 degrees pronation and 10 degrees pronation (*P*=.036).

During the single leg squat, regardless of foot position, the gluteus maximus had the largest %MVC (86.220) with gluteus medius have the second largest % MVC (83.840) on average for all positions. The anterior tibialias having the smallest % MVC on average for all positions (60.224). The anterior tibialis had the highest %MVC at 10 degrees of pronation (64.920), lateral gastrocnemius had the highest at 10 degrees pronation (88.490), rectus femoris was highest at 5 degrees supination (74.120), biceps femoris greatest at 10 degrees supination (87.690), gluteus maximus greatest at 10 degrees pronation (101.480).

Table 1

Muscle	N	Chi-square	df	P
Anterior Tibialis	10	2.240	4	0.692
Lateral Gastrocnemius	10	12.56	4	0.014*
Rectus Femoris	10	5.246	4	0.263
Biceps Femoris	10	9.680	4	0.046*
Gluteus Medius	10	6.080	4	0.193
Gluteus Maximus	10	22.81	4	< .001**

Friedman's Test for differences in EMG activity between foot positions for each of the 6 muscles.
* $P < .05$

** $P < .001$

Table 2 – 1: Means and Standard Deviations for Anterior Tibialis in Each Position

Position	Mean	Standard Deviation
Standard	62.4500	11.05976
5 degrees supination	55.1500	17.38162
10 degrees supination	58.2500	10.97788
5 degrees pronation	60.3500	14.35752
10 degrees pronation	64.9200	19.27686

Mean and standard deviation values for RM ANOVA of the tibialis anterior in each foot position. The mean is expressed as %MVC.

Table 2-2: Means and Standard Deviations for Lateral Gastrocnemius in Each Position		
Position	Mean	Standard Deviation
Standard	74.1600	7.02032
5 degrees supination	76.9700	22.38859
10 degrees supination	74.2200	13.29969
5degrees pronation	82.9200	11.43871
10 degrees pronation	88.4900	20.72038

Mean and standard deviation values for RM ANOVA of the lateral gastrocnemius in each foot position. The mean is expressed as % MVC.

Table 2-3: Means and Standard Deviations for Rectus Femoris in Each Position		
Position	Mean	Standard Deviation
Standard	66.8400	8.87170
5 degrees supination	74.1200	31.97064
10 degrees supination	72.4800	31.55605
5 degrees pronation	70.9500	28.14227
10 degrees pronation	70.1200	33.81334

Mean and standard deviation values for RM ANOVA of the rectus femoris in each foot position. The mean is expressed as % MVC.

Table 2-4: Means and Standard Deviations for Biceps Femoris in Each Position		
Position	Mean	Standard Deviation
Standard	68.4000	7.14967
5 degrees supination	76.4000	26.53446
10 degrees supination	87.6900	29.47422
5 degrees pronation	81.8100	16.66890
10 degrees pronation	87.1100	20.43828

Mean and standard deviation values for RM ANOVA of the biceps femoris in each foot position. The mean is expressed as % MVC.

Table 2-5: Means and Standard Deviations for Gluteus Medius in Each Position

Position	Mean	Standard deviation
Standard	75.73	8.275
5 degrees supination	82.02	18.36
10 degrees supination	85.80	17.67
5 degrees pronation	86.91	13.53
10 degrees pronation	88.74	14.34

Mean and standard deviation values for RM ANOVA of the gluteus medius in each foot position. The mean is expressed as % MVC.

Table 2-6: Means and Standard Deviations for Gluteus Maximus

Position	Mean	Standard Deviation
Standard	68.6700	5.41542
5 degrees supination	81.7700	16.31421
10 degrees supination	91.9700	29.94955
5 degrees pronation	87.2100	16.35240
10 degrees pronation	101.4800	22.43251

Mean and standard deviation values for RM ANOVA of the glut max in each foot position. The mean is expressed as % MVC.

CHAPTER V

DISCUSSION

Our research focused on the subtalar joint and if muscle activity changed in supination, pronation or neutral (standard). We could analyze the effect of distal joint positioning on proximal muscle activity. Muscle activity tended to vary the most during the pronated foot positions as compared to activity in the neutral position. Ten degrees pronation, on average, had the highest % MVC for four of the six muscles including anterior tibialis, lateral gastrocnemius, gluteus medius, and gluteus maximus. The standard foot position had the lowest % MVC for all of the muscles except anterior tibialis which had the lowest % MVC at 5 degrees supination. Muscle activity is highest in the pronated foot position. This could be due to poor foot positioning which requires the muscles above the subtalar joint to fire more for stabilization. The joints, muscles, and ligaments could all experience increased stress. This may support that pronation is a less optimal foot position and requires greater muscle contraction for stability. If an athlete has poor strength, he or she may not be able to produce a strong enough muscle contraction to stabilize the proximal joints which may place the ACL vulnerable to injury.

The researchers investigated the effect of foot position on muscle activity above the joint to speculate if foot position could increase or decrease the risk of ACL injury. The % MVC at each position for each muscle was compared to an average MVC value. The foot positions with large variability in data collected could be due to subject's difficulty to maintain balance in these positions or from the subject using compensation patterns to complete the single leg squat. A learning curve could have occurred. The subjects completed at least 10 single leg squats at each foot position and thus would have time to figure out the surface, adjust their body accordingly, and prevent testing in the true targeted foot position. The % MVC did increase for the pronated foot positions and certain muscles showed dominance but due to the high variability and small sample size, this may not be accurate.

A couple limitations existed in our study. We did not control how deeply each subject squatted so ROM was variable among subjects and within subjects as well which likely affected muscle activity and body positioning. ROM was not controlled for but the ideal is between 50-60 degrees as based on previous studies. Our hope is that our subjects were in this ideal zone for a majority of the squats. Fatigue could also impact the quality of the squat and thus the data, especially for the last incline (random incline order should minimize the overall impact on our data) or for the fourth and fifth squats in each position. Trunk lean and pelvis positioning could have influenced the magnitude of muscle activation. Subjects were allowed to change their body position in order to maintain balance and not all subjects leaned the same way or at all. This variable could be more controlled in the future. A metronome may also have limited our study because it is likely not the speed used to complete daily activities and thus may not be applicable to the sports setting; however, it offers control for our study as simulating true movement speed would be difficult. A large number of researchers (8 people) were involved with project set up, which could impact error as well. Most ACL injuries occur during a jump landing or a cutting maneuver and our study looked at muscle activity with the foot already firmly planted. This may limit the ability to relate our study to a dynamic movement injury but is good to see the change in muscle activity with different foot positions.

Component movements below the joint which contribute to knee valgus include tibial internal rotation and foot pronation. Our study supports the hypothesis that pronation does impact the muscle activity above the subtalar joint. This helps to explains why an orthotic device, if used correctly and when needed, can help decrease risk of injury at the knee. A medially-posted orthotic device can decrease both tibial internal rotation and foot pronation which would decrease knee valgus, making the knee less susceptible to ACL stress. In a study assessing the use of an orthosis, significant differences were found in knee and ankle measures at both initial contact and maximum position when the orthosis was worn with no differences between dominant and nondominant sides.[1] When a five degree medial post was placed in the shoe, knee valgus angles decreased. Since knee valgus is a key position seen with ACL injuries, I find this to be of benefit for athletes who pronate. Females may be at a higher risk due to anatomical differences in body structures, changes in hormones, decreased strength in key muscle areas, and poor neuromuscular control. Females should focus on having a balanced hamstring/quadriceps contraction which may help a female land with more knee flexion and less valgus alignment.

Due to a high prevalence of ACL injuries, action needs to be taken to decrease the risk and occurrence of injuries, especially females. Posture screenings should be conducted in all athletes; those who display genu recurvatum with subtalar joint overpronation may be at increased risk of injury during dynamic movements.[15] Other factors which should be screened in female athletes include prior ipsilateral ankle sprain, greater generalized laxity in the lower extremity, and decreased iliotibial band flexibility, as these can increase risk of ACL injury.[32] Squat strength does not appear to be a good screening tool; however, measuring hip abductor strength or external rotator strength may be a good screening tool to identify at-risk athletes and should be done.[71] If these muscles are weak, they should be the target for an athlete's strengthening program.

During sidestep cutting maneuvers, athletes want to focus on cutting with small knee valgus angles, minimal ankle pronation, and a narrow stance (particularly for cuts that are performed with high approach speed and sharp direction changes) in order to optimize performance and prevent injury.[70] An agility training program focused on increasing neuromuscular hamstring strength and activity for a balanced quadriceps/hamstring contraction could protect the ACL. It is important for females to strengthen both their gluteal maximus and medius and their hamstrings to minimize quadriceps dominance and a knee valgus position. Impaired neuromuscular control can contribute to ACL injury, training programs should include and emphasize neuromuscular control as well as proprioceptive training.[3,15,33,59] Training programs should address the four dysfunctional movement patterns mentioned earlier, including ligament, quadriceps, leg, and trunk dominance.[64] A prevention program focusing on strengthening, balance, jump-landing techniques, and basketball skills with instruction to avoid excess lumbar lordosis, rear axial weight bearing, hip adduction, and knee valgus can improve alignment and decrease strain on the ACL .[72] Essential components of a prevention program, as identified by Bien,[19] were hip and hamstring training, core stabilization, plyometrics, balance, agility, neuromuscular training, and stretching. Agility programs can increase medial hamstring activity as well.[50]

ACL deficient patients exhibit gait changes and make biomechanical adaptations in order to complete their daily activities. By losing their ACL, individuals exhibit anteroposterior knee instability as well as rotatory knee instability and adapt to a pivot-shift avoidance gait. By changing their gait they can prevent anterolateral rotatory knee instability, reducing internal knee joint rotation especially during terminal stance. The relationship between strength and injury is not fully understood but decreased strength in particular muscle groups may place the individual prone to certain injuries.[5] Athletes who tear their ACL one time, are at increased risk of another tear and need to be educated on prevention. They should be evaluated for risk factors which could have placed them at a higher risk of their first tear and then be placed on a prevention program to prevent reoccurrence.

Based on reviewing the literature and the results of our study, foot position does impact muscle activity and can change joint alignment above the foot. Several risk factors exist for ACL injury and measures should be taken to try to limit/control these as much as possible. Relationship between foot and knee frontal plane motion during both static and dynamic tasks should be investigated further.

CHAPTER VI

CONCLUSION

Muscle activity changes regarding foot positions were statistically significant for the lateral gastrocnemius, biceps femoris, and gluteus maximus but not found to be significant for the tibialis anterior, rectus femoris, or gluteus medius. These results have both skew and kurtosis data and the differences may be due to the large variability in our study versus actual statistical significance. Muscle activity tended to vary the most during the pronated foot positions as compared to activity in the neutral position. Increased muscle activity seen in pronation may be needed to increase stability due to increased forces on the knee in this position. This current study may help explain why orthotic devices can improve muscle performance and prevent lower extremity injuries (including at the knee). We had large variability in our results and future studies should focus on larger sample size, specific age groups, and a standardized procedure. Foot position may change the muscle activity above that joint and could impact the risk of ACL, but future studies are needed to confirm the significance of this finding.

APPENDIX

Tables 3: Repeated Measures ANOVA . Results for Comparison of EMG Activity Between Positions, for Each of 6 Muscles.

Table 3-1 RM ANOVA Results: Anterior Tibialis						
	Type III Sum of Squares	df	Mean Square	F	P	Power
Factor I: Position	566.655	4	141.664	.827	.517	.238
Error	6165.513	36	171.264			
Mauchley's Test of Sphericity demonstrating non-significance (p=.517>.05)						

Table 3-2 RM ANOVA Results: Lateral Gastrocnemius						
	Type III sum of squares	df	Mean square	F	P	Power
Factor I: Position	1552.019	4	388.005	3.060	.029	.751
Error	4564.565	36	126.793			
Mauchley's Test of Sphericity demonstrating significance (p=.029<.05)						

Table 3-3 RM ANOVA Results: Rectus Femoris						
	Type III Sum of Squares	df	Mean square	F	P	Power
Factor I: Position	299.593	4	74.898	.335	.853	.689
Error	8053.567	36	223.710			
Mauchley's Test of Sphericity demonstrating non-significance (p=.852>.05)						

Table 3-4 RM ANOVA Results: Biceps Femoris						
	Type III Sum of Squares	df	Mean Square	F	P	Power
Factor I: Position	2600.867	4	650.217	2.727	.044	.695
Error	8582.189	36	238.394			
Mauchley's Test of Sphericity demonstrating significance (*p*=.044<.05)						

Table 3-5 RM ANOVA Results: Gluteus Medius						
	Type III sum of squares	df	Mean square	F	P	Power
Factor I: Position	1063.610	4	265.903	2.695	.046	.687
Error	3551.358	36	98.649			
Mauchley's Test of Sphericity demonstrating significance (p=.046<.05)						

Table 3-6 RM ANOVA Results: Gluteus Maximus						
	Type II sum of squares	df	Mean square	F	P	Power
Factor I: Position	5947.152	4	1486.788	8.696	<.001	.997
Error	6155.176	36	170.977			
Mauchley's Test of Sphericity demonstrating significance (p=.001<.05)						

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