THE EFFECTS OF LIMITED ANKLE DORSIFLEXION RANGE OF MOTION ON KNEE AND ANKLE KINEMATICS

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Abstract

KARLI DILL: The Effects of Limited Ankle Dorsiflexion Range of Motion on Knee and Ankle Kinematics
(Under the direction of Darin Padua)

Ankle dorsiflexion (DF) range of motion (ROM) may influence movement variables that are known to impact ACL loading, such as knee valgus and knee flexion. Research has not identified individuals with limited and normal DF to investigate the relationship between DF assessments and movement patterns. DF ROM (knee straight, knee bent), weight bearing lunge technique (WBLT), and anterior/posterior (A/P) talar glide were assessed. Participants were grouped into limited and normal groups based on knee straight DF ROM. Knee and ankle kinematics were assessed during three dynamic movements (OHS, SLS, JL). Three separate ANOVA's for task and Pearson correlations between ROM and ankle kinematics were performed. There were no kinematic differences between the limited and normal groups during any of the tasks. The WBLT strongly correlated with ankle DF displacement during the OHS and SLS. Therefore, the WBLT may be more representative of the amount of DF range of motion during movement.

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Chapter I

Introduction

The incidence of anterior cruciate ligament injury (ACL) is concerning. Approximately 80,000-250,000 anterior cruciate ligament injuries occur in the United States annually with the majority of these injuries occurring in individuals ages 15 to 25 who participate in sports (Griffin, Agel et al. 2000; Griffin, Albohm et al. 2006). In addition, 70% of ACL injuries result from non-contact mechanisms, defined as no contact with another player or piece of equipment, such as landing from a jump and decelerating (Boden, Griffin et al. 2000; Hewett, Myer et al. 2006).

Injury to the ACL comes with a heavy personal, financial, and physical burden. Not only does the individual have to endure a loss of time from his/her sport, they also have to undergo a surgical procedure, and complete a very demanding rehabilitation to return to their sport. The surgical procedure and rehabilitation can become costly, placing an even greater burden on the athlete. The average cost of surgical repair is approximately $17,000 per incident with annual costs approaching one billion dollars per year (Griffin, Agel et al. 2000). ACL injuries can also have a long-term impact, particularly in terms of contributing to the onset of knee osteoarthritis. Female soccer players who sustained an ACL tear were examined 12 years after injury with radiography and self-administered health questionnaires. The results indicated that 51% of these previously injured individuals had radiographic knee osteoarthritis and 75% of them reported having knee symptoms that affected their quality of life (Lohmander, Östenberg et al. 2004). Male soccer players were also examined in a similar fashion 14 years after injury with results that showed 78% of these athletes had radiographic osteoarthritis (von Porat, Roos et al. 2004). Re-injury of the ACL is also a concern for athletes with studies suggesting that previous history of injury places an athlete at a higher risk for re-injury (Orchard, Seward et al. 2001), and the risk of injury to the contralateral knee is equal to the risk of re-injury of the same knee (Salmon, Russell et al. 2005; Wright, Dunn et al. 2007). Previous history of ACL ruptures places an athlete at higher risk for injury and not only affects the short-term career of an athlete, but their quality of life years after their athletic career is over. This makes evident the need for continuing research to better understand risk factors and mechanisms associated with ACL injury and re-injury; and direct injury prevention programming to decrease the incidence of ACL injury.

Non-contact injury mechanisms, such as plant-and-cut maneuvers, landing from a jump, landing on a single limb, and deceleration (Olsen, Myklebust et al. 2004; Faunø and Wulff Jakobsen 2006) account for the majority of ACL injuries (Arendt, Agel et al. 1999; Agel, Arendt et al. 2005). Epidemiological data presented by Agel and Arendt et al. (Agel, Arendt et al. 2005) highlighted that non-contact injury mechanisms, defined by no contact with another player or piece of equipment, accounted for nearly twice the amount of ACL injuries in collegiate men’s and women’s soccer and basketball players. The high incidence of non-contact injury is driving ongoing research toward investigating possible biomechanical and neuromuscular risk factors that could contribute to non-contact ACL injury.

Non-contact injuries have been suggested to occur in a position of combined hip internal rotation and adduction, knee valgus collapse, a less flexed knee, with either external or internal rotation on the tibia and a pronated foot (Ireland 1999; Olsen, Myklebust et al. 2004). Knee valgus and knee flexion angles have been demonstrated to place greater strain on the ACL through cadaveric and in-vivo studies. A study performed by Withrow et al. (Withrow, Huston et al. 2006) reported results of a 30% increase in ACL strain with an impulsive knee valgus moment during a simulated jump landing. Knee flexion angle was studied in-vivo during a double leg squat and flexion-extension exercises, with greater ACL strain observed when the knee was in a less flexed position during both exercises (Beynnon, Fleming et al. 1995; Beynnon, Johnson et al. 1997). These findings support the claim that knee valgus and knee flexion angles can put the ACL under greater strain, therefore increasing an individual's risk for injury.

Due to the growing body of literature that suggests joint position, knee flexion angle and knee valgus angle, can influence strain on the ACL, it is important to identify factors that may lead to these potentially hazardous positions. To explore the possible contributors to knee valgus, a large body of research has focused on kinematics and strength at the hip. Lesser gluteus maximus recruitment (Hollman, Ginos et al. 2009), lesser hip external rotation strength (Willson, Ireland et al. 2006), greater internal knee adduction moments (Pollard, Sigward et al. 2010), and lesser hip abduction strength (Claiborne, Armstrong et al. 2006; Hollman, Ginos et al. 2009) have been suggested to contribute to greater knee valgus along with greater hip adduction angles (Hollman, Ginos et al. 2009), lesser hip flexion angles (Pollard, Sigward et al. 2010), and greater hip internal rotation angles (Pollard, Sigward et al. 2010). Kinematics at the knee, including a lesser knee flexion angle, has also been proposed to contribute to greater knee valgus compared to greater knee flexion angles (Pollard, Sigward et al. 2010). This body of research supports the theory that what occurs at the hip and knee can contribute to knee valgus. Current research has begun to look at factors at the ankle that may contribute to knee valgus such as ankle dorsiflexion range of motion. This relationship, however, remains unclear with contradicting results. Some studies have observed lesser ankle dorsiflexion range of motion to be associated with medial knee displacement (Bell, Padua et al. 2008; Sigward, Ota et al. 2008), while other studies have indicated that greater dorsiflexion range of motion is associated with greater knee valgus (Zeller, McCrory et al. 2003; Kernozek, Torry et al. 2005).

The increased load on the ACL with a shallower knee flexion angle has been associated with an increase in quadriceps contraction (Durselen, Claes et al. 1995; DeMorat, Weinhold et al. 2004; Withrow, Huston et al. 2006). Quadriceps contraction causes anterior translation of the tibia on the femur due to the attachment point of the patellar tendon on the tibial tuberosity. The resultant anterior tibial translation places a shear force on the ACL (Beynnon, Fleming et al. 1995) and it has been demonstrated that larger knee flexion angles decrease activation of the quadriceps resulting in less strain on the ACL (Blackburn and Padua 2009). Therefore, it would be beneficial to utilize a greater amount of knee flexion during athletic tasks such as landing from a jump to decrease strain on the ACL. A greater knee flexion angle has been demonstrated to occur with greater trunk and hip flexion, and a reduction in vertical ground reaction forces during a drop landing (Blackburn and Padua 2008; Blackburn and Padua 2009). These results may be due to the ability of the joints to work in synchrony to absorb landing forces through greater flexion angles and if this is the case, flexion at the ankle may also be a contributing factor.

Ankle dorsiflexion range of motion has been proposed as an influential factor for knee valgus and knee flexion angles but there has been limited research in this area. Bell, Padua et al. (Bell, Padua et al. 2008) studied individuals with medial knee displacement, which is a clinical observation of dynamic valgus collapse, and observed subjects displaying medial knee displacement during an overhead squat had approximately 20% less passive dorsiflexion, assessed prior to testing, than subjects who did not display medial knee displacement. Furthermore, the medial knee displacement shown during the overhead squat was corrected with a heel lift. This may have occurred due to the increased dorsiflexion range of motion that the subjects could utilize when they had the assistance of the heel lift. In addition, lesser dorsiflexion range of motion has been associated with greater frontal plane knee excursion during a drop landing in young female soccer players (Sigward, Ota et al. 2008) and with a lesser knee flexion angle during a jump landing task (Fong, Blackburn et al. 2011). In contrast, results from two studies suggest that females with greater knee valgus during a single-leg squat and drop landing displayed greater dorsiflexion range of motion measured during each task (Zeller, McCrory et al. 2003; Kernozek, Torry et al. 2005). This body of research suggests that ankle dorsiflexion range of motion may contribute to the amount of knee valgus and knee flexion an individual utilizes, but the relationship is unclear. The discrepancy in the current body of literature requires ongoing research to investigate the effects of dorsiflexion range of motion on knee kinematics during movement.

The contrasting results in previous research may be due to the different techniques used to assess dorsiflexion range of motion and possibly the tasks utilized. Some researchers assessed passive dorsiflexion range of motion prior to the performance of their various tasks (Bell, Padua et al. 2008; Sigward, Ota et al. 2008), while others assessed peak dorsiflexion angles achieved during the tasks performed (Zeller, McCrory et al. 2003; Kernozek, Torry et al. 2005). If passive dorsiflexion range of motion, peak dorsiflexion range of motion, and A/P talar glide were all assessed, a clearer picture may be drawn from the data. This may also identify whether passive range of motion measurements correlate with functional measurements such as peak ankle dorsiflexion.

To better understand the effect of dorsiflexion range of motion on knee kinematics, subjects with limited dorsiflexion range of motion and normal dorsiflexion range of motion should be compared. The comparison of a limited and normal group could more clearly define whether there are differences between the two groups and where those differences exist, establishing a more valid relationship between dorsiflexion range of motion and knee kinematics.

The identification of ACL risk factors is important in preventing further injury. Excessive knee valgus and minimal knee flexion angles have been suggested as risk factors for ACL injury and dorsiflexion range of motion's relationship with these two factors has been researched, but results are unclear. Therefore, the purpose of this study is to identify differences in lower extremity kinematics in subjects with limited dorsiflexion range of motion compared to subjects with normal dorsiflexion range of motion and secondarily, to determine whether different dorsiflexion range of motion measurements are correlated.

Independent Variables

- Group: Limited dorsiflexion range of motion vs. normal dorsiflexion range of motion
- Task: overhead squat (OHS), single leg squat (SLS), jump landing task (JL)

Dependent Variables

- Ankle dorsiflexion measure with the knee straight
- Ankle dorsiflexion measured with the knee bent to 90º
- Weight bearing lunge measurement
- A/P talar glide
- Peak knee valgus
- Knee valgus displacement
- Medial knee displacement
- Peak knee flexion angle
- Knee flexion displacement
- Ankle dorsiflexion displacement

Research Questions

- RQ 1) Do subjects with limited (≤10º) dorsiflexion ROM display greater peak knee valgus angles, greater knee valgus displacement, greater medial knee displacement, lesser peak knee flexion angles, lesser knee flexion displacement, lesser ankle dorsiflexion displacement, and lesser peak ankle dorsiflexion angles in comparison to subjects with normal (≥20º) dorsiflexion ROM during a SLS, an OHS, and a JL task?
- RQ 2) Is there a correlation between the dorsiflexion range of motion and measurements with the knee straight, knee bent to 90º, using the weight bearing lunge technique, peak ankle dorsiflexion reached during each task, and A/P talar glide?

Null Hypotheses

- RQ 1) There will be no difference between subjects with limited dorsiflexion and subjects with normal dorsiflexion with respect to peak knee valgus angle, knee valgus displacement, peak knee flexion angle, knee flexion displacement, medial knee displacement, ankle dorsiflexion displacement, and peak ankle dorsiflexion during a SLS, OHS, and JL.
- RQ 2) There will be no correlation between the dorsiflexion range of motion measurements with the knee straight, knee bent to 90º, using the weight bearing lunge technique, peak dorsiflexion reached during each task, and A/P talar glide.

Research Hypotheses

- RQ 1) In comparison to subjects with normal dorsiflexion ROM, during the SLS , OHS, and JL task, subjects with limited dorsiflexion ROM will display significantly greater peak knee valgus angles, knee valgus displacement, and medial knee displacement, and significantly lesser peak knee flexion angles, knee flexion displacement, ankle dorsiflexion displacement, and peak ankle dorsiflexion angles.
- There will be a strong positive correlation between dorsiflexion measured with the knee straight, knee bent to 90º, using the weight bearing lunge technique, and peak dorsiflexion during each task.

Operational Definitions

- Weight bearing dorsiflexion range of motion: Measured using a weight bearing lunge technique (Bennell, Talbot et al. 1998)
- Gastrocnemius dorsiflexion range of motion: Measured supine with the knee straight using a plastic manual goniometer
- Soleus dorsiflexion range of motion: Measured supine with the knee at 90 degrees of flexion with a plastic manual goniometer
- A/P talar glide: Measured using a portable instrumented ankle arthrometer. Measurements quantify the A/P load-displacement and Inv/Ev rotational laxity characteristics of the ankle-subtalar joint complex
- Limited dorsiflexion range of motion: Less than or equal to 5 degrees of passive dorsiflexion measured with the knee straight (Moseley, Crosbie et al. 2001)
- Normal dorsiflexion range of motion: Greater than or equal to 15 degrees of passive dorsiflexion measured with the knee straight (Moseley, Crosbie et al. 2001)
- Overhead Squat: Performed with toes pointing straight ahead, feet shoulder width apart, arms extended vertically overhead, squatting to at least 60 degrees while keeping the heels on the ground
- Single Leg Squat: Performed on the dominant limb with the toes facing forward, hands on the hips, opposite foot raised approximately 10 cm off the ground, squatting to at least 60 degrees while keeping the heel on the ground

- Squat descent phase: Initial onset of knee flexion to peak knee flexion.
- Jump landing task: Jump from a 30cm box placed a distance of 50% of standing height away from the landing surface, and immediately jumping vertically, as high as possible
- Initial Ground Contact: The time point when vertical ground reaction force exceeds 10N.
- Jump landing descent phase: the time of initial ground contact to peak knee flexion
- Peak knee valgus angle: Maximum point of knee motion in the negative direction about the x-axis in the frontal plane during the decent phase of each task
- Knee Valgus Displacement: Initial knee valgus angle subtracted from the peak knee valgus angle achieved during the decent phase of each task.
- Medial knee displacement: The total straight-line displacement of the knee joint center along the y-axis, measured in centimeters from the initial point of the knee joint center, to the peak medial placement of the knee joint center during the descent phase of each task
- Peak knee flexion angle: Maximum point of motion of the shank relative to the thigh in the positive direction about the y-axis in the sagittal plane during the decent phase of each task
- Knee flexion displacement: Initial knee flexion angle subtracted from the peak knee flexion angle during the descent phase

- Ankle dorsiflexion displacement: The initial degree of dorsiflexion subtracted from the peak dorsiflexion angle reached during each task
- Dominant Limb: Limb used to kick a ball for maximum distance
- Physically Active: Participates in physical activity at least three days a week for 30 minutes

Assumptions

- Subjects will honestly report history of injury
- Instruments and investigator will be reliable
- Sample will accurately represent the population

Delimitations

- Subjects will be physically active and healthy individuals selected from the community of The University of North Carolina at Chapel Hill
- Subjects will not have a history of lower extremity surgery within the past two years
- Subjects will not have a history of knee or ankle injury that has kept them out of physical activity for two or more days in the past six months.
- Data was collected on the dominant limb of each subject
- Subjects will be given a maximum of five practice trials for each task
- All subjects will perform the overhead squat and single leg squat to at least 60 degrees of knee flexion

Limitations

- The hip can influence knee valgus angles, knee flexion angles, and medial knee displacement, but will not be analyzed.
- Inclusion of physically active individuals may limit the generalizability to other populations, such as an injured population.
- Subjects will complete a self-reported medical history

Chapter II

Review of Literature

Introduction

Approximately 80,000-250,000 anterior cruciate ligament injuries (ACL) occur in the United States annually with the majority of these injuries occurring in individuals ages 15 to 25 who participate in sports (Griffin, Agel et al. 2000; Griffin, Albohm et al. 2006). With a cost of $17 million per patient (Hewett, Lindenfeld et al. 1999) the expenses for ACL injury can quickly compound, approaching one billion dollars per year (Griffin, Agel et al. 2000). As a result of the high incidence and cost of ACL injury, the identification of risk factors for this injury has been a focus of ongoing research. The understanding of injury risk factors and mechanisms will help shape the injury prevention strategies that are implemented with a goal of decreasing the incidence of ACL rupture.

The purpose of this review is to present background information on the knee, proposed injury mechanisms, and implications at the hip, knee, and ankle that contribute to the risk of ACL injury. Research on kinematics at the ankle will be of particular interest because of the inconclusive results of this research.

Relevant Anatomy

The tibiofemoral joint along with the patellofemoral joint formulate what is referred to as the knee joint. The convex femoral condyles, which are separated by the intercondylar notch, articulate with the medial and lateral condyles of the tibia, also known as the tibial plateau. This articulation is the tibiofemoral joint. This joint is supported by a joint capsule and four main ligaments, the medial collateral, lateral collateral, anterior cruciate and posterior cruciate ligaments (Seeley, Stephens et al. 2004). On the surface of the medial and lateral condyles of the tibia there are menisci that provide cushioning, stabilization, and proprioception for the knee joint while also guiding arthrokinematic motion at the knee. Flexion, extension, internal, and external rotation are motions that occur at the tibiofemoral joint. These motions are restricted by the soft tissue structures as well as the bony congruency of the joint (Neuman 2010).

The anterior cruciate ligament attaches to the anterior intercondylar area on the tibia and runs posterior, superior, and laterally to attach to the medial aspect of the lateral femoral condyle. To reach the lateral femoral condyle the ligament must run through the intercondylar notch of the femur. The ligament is comprised of two bundles, the anterior-medial bundle and the posterior-lateral bundle, named by their attachment points on the tibia. The primary mechanism of the ACL is to minimize anterior translation of the tibia relative to the femur. (Neuman 2010).

The major muscles that contribute to motion at the knee include the quadriceps, hamstrings, and gastrocnemius. The quadriceps consists of the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius all of which act primarily as knee extensors (Seeley, Stephens et al. 2004). They provide stabilization of the knee through isometric contraction and they control the amount of knee flexion that is reached during activities such as jumping through eccentric contraction (Neuman 2010). The hamstrings group on the posterior thigh consists of the biceps femoris, semimembranosis, and semitendinosis, all of which act as knee flexors and hip extensors (Seeley, Stephens et al. 2004). These muscles also produce rotational movement at the knee with the biceps femoris creating external rotation of the tibia, and the semimembranosis and semitendinosis creating internal rotation of the tibia. The hamstrings work as antagonists against the quadriceps, thus they work eccentrically to control knee extension (Neuman 2010). The activity of the quadriceps and hamstrings can have implications in ACL injury. Greater strain on the ACL has been observed in shallow knee flexion angles with activation of the quadriceps due to the anterior tibial translation that occurs with quadriceps contraction (Durselen, Claes et al. 1995; DeMorat, Weinhold et al. 2004). Due to the antagonistic role of the hamstrings against the quadriceps, hamstring strength (Myer, Ford et al. 2009) and stiffness (Blackburn, Norcross et al. 2011) have been suggested to play a role in decreasing anterior tibial shear force.

Anatomical factors such as tibial slope and femoral intercondylar notch width have also been proposed to have implications for ACL injury (Souryal and Freeman 1993; LaPrade and Burnett 1994; Giffin, Vogrin et al. 2004). Prospective studies have indicated that individuals with a narrow intercondylar notch size are at greater risk for ACL injury (Souryal and Freeman 1993; LaPrade and Burnett 1994). This may be due to the impingement of the ACL over the medial aspect of the lateral femoral condyle in a stenotic intercondylar notch (LaPrade and Burnett 1994). An increased tibial slope through osteotomy resulted in an anterior shift of the tibia in the resting position especially with the knee in extension. This also resulted in greater anterior tibial translation at 30 and 90 degrees of knee flexion (Giffin, Vogrin et al. 2004). The greatest strain on the ACL has been observed with anterior tibial force (Markolf, Burchfield et al. 1995), and if increased tibial slope places the tibia in a more anterior position, this may be detrimental to the ACL.

Non-Contact Knee Injuries

Non-contact mechanisms, defined by no contact with another player or piece of equipment, have been found to cause approximately 70% of ACL injuries (Arendt, Agel et al. 1999; Boden, Dean et al. 2000; Agel, Arendt et al. 2005; Hewett, Myer et al. 2006). Epidemiological data presented by Agel and Arendt et al. (Agel, Arendt et al. 2005) revealed non-contact injury mechanisms accounted for nearly twice the amount of ACL injuries in collegiate men's and women's soccer and basketball players. These non-contact injuries have been found to occur during plant-and-cut maneuvers, landing on a single limb, decelerating, and landing from a jump (Ford, Myer et al. 2003; Olsen, Myklebust et al. 2004).

Ireland et al. (Ireland 1999) described hip internal rotation and adduction, combined with a more extended knee, knee valgus, and tibial external rotation on a pronated and externally rotated foot as a "position of no return" contributing to non-contact ACL injury. In addition, video analysis was performed on 20 ACL injuries that occurred in women's team handball with results showing ACL injury occurred when landing with the knee near full extension, with valgus collapse, and internal or external rotation on the tibia (Olsen, Myklebust et al. 2004). Markolf et al. (Markolf, Burchfield et al. 1995) used cadaveric knees to investigate the biomechanics at the knee that place the greatest strain on the ACL. The study suggests the greatest loads on the ACL occur with anterior tibial force combined with internal tibial torque at near extension, and anterior tibial force combined with a valgus moment.

Knee Valgus

A number of research studies have implicated knee valgus as a position of injury for the ACL (Ireland 1999; Olsen, Myklebust et al. 2004). Research has suggested that injury may occur in this position because of the increased strain placed on the ligament. Withrow et al. (Withrow, Huston et al. 2006) used 10 cadaveric knees and applied an impulsive valgus moment through dropping a 150N weight onto an impact rod that translated the force through the femur to the knee. Strain on the ACL was measured in the anteromedial bundle of the ACL and it was found to be 30% greater with the combined application knee valgus and flexion compared to flexion alone. Markolf et al. (Markolf, Burchfield et al. 1995) used 14 cadaveric knees and manipulated them with a loading device that placed loads on the tibia which translated to the knee. Anterior tibial force combined with valgus moment placed greatest strain on the ACL. Although these studies placed loads on the ACL in different conditions, internal knee valgus moment was shown to increase ACL strain in both conditions (Markolf, Burchfield et al. 1995; Withrow, Huston et al. 2006). This demonstrates the significance of knee position, particularly knee valgus, on ACL strain in relation to potential injury.

Research also proposed that kinematics at the hip and knee may contribute to knee valgus. Hip adduction angle has been demonstrated to be positively correlated with knee valgus during a single leg step down task (Hollman, Ginos et al. 2009). These results are in congruence with a study performed on female soccer athletes performing a side-step cutting maneuver, which also demonstrated greater hip adduction angles in females who had previously been shown to demonstrate greater knee valgus. This study also observed that these female soccer athletes displayed greater hip internal rotation angles (Pollard, Sigward et al. 2007). Knee flexion angle has also been indicated as a contributing factor to knee valgus with female soccer players displaying low knee flexion angles and greater knee valgus (Pollard, Sigward et al. 2010). This may be due to the absorption of forces through the motion that occurs at the knee. If there is lesser motion in the sagittal plane to absorb forces, compensations may occur in the frontal plane, therefore contributing to knee valgus. Recently, dorsiflexion range of motion at the ankle has been implicated as a possible contributing factor to knee valgus, but the results of this research are unclear. Studies have observed lesser dorsiflexion range of motion with greater knee valgus (Bell, Padua et al. 2008; Sigward, Ota et al. 2008). In contrast, studies have also suggested greater dorsiflexion range of motion may contribute to greater knee valgus (Zeller, McCrory et al. 2003; Kernozek, Torry et al. 2005)

Knee Flexion

Greater loads on the ACL have been observed in lesser knee flexion angle during landing (Beynnon, Fleming et al. 1995; Durselen, Claes et al. 1995; Beynnon, Johnson et al. 1997; DeMorat, Weinhold et al. 2004; Li, DeFrate et al. 2005). Quadriceps activation is an important factor when discussing knee flexion angle and strain placed on the ACL because of its insertion on the tibia. Anterior tibial force places the greatest load on the ACL (Markolf, Burchfield et al. 1995) and anterior tibial translation is created with a contraction of the quadriceps (DeMorat, Weinhold et al. 2004). Cadaveric and in-vivo studies have been performed to analyze the effect of knee flexion angle and quadriceps activation on ACL strain. Cadaveric studies have suggested that lesser knee flexion angles combined with simulated quadriceps activation produce greater strain on the ACL compared to angles of greater knee flexion (Durselen, Claes et al. 1995; DeMorat, Weinhold et al. 2004). Studies performed in-vivo have also observed greater strain on the ACL in lesser knee flexion angles. Beynnon et al. (Beynnon, Fleming et al. 1995) analyzed ACL strain in vivo during active flexion and extension of the knee, and with isometric contractions of the quadriceps at different angles of knee flexion. ACL strain increased as the knee reached lesser flexion, with the greatest strain being produced at 15 and 30 degrees of knee flexion combined with isometric quadriceps contraction. A squatting exercise was analyzed in the same manner to determine ACL strain values during the exercise. This study also resulted in findings that suggest greater ACL strain at angles of lesser knee flexion (Beynnon, Johnson et al. 1997). These combined results from cadaveric and in-vivo studies produce strong evidence that lesser knee flexion angles combined with quadriceps contraction can increase strain on the ACL. These findings have relevant implications to the kinematics used in physical activity and sport and an individual's risk for ACL injury.

The hamstrings have been theorized to work synergistically with the ACL to prevent anterior tibial translation (More, Karras et al. 1993). A study performed by Myer et al. (Myer, Ford et al. 2009) prospectively collected isokinetic quadriceps and hamstring strength on female athletes who subsequently suffered ACL rupture. These subjects were compared to matched female and male controls with results demonstrating injured athletes had 15% less hamstring strength than male controls. However, quadriceps strength did not differ between injured females and the controls. Hamstring loads have been suggested to decrease anterior tibial translation during flexion in a cadaveric study (Renström, Arms et al. 1986). These cadaveric studies have also examined the loads placed on the ACL during hamstring and quadriceps co-activation. It has been proposed that ACL load is greater from full extension to 30 degrees of flexion with applied hamstring and quadriceps activation. However, in flexion angles greater than 30 degrees, ACL stain was not different from that measured during passive motion (Renström, Arms et al. 1986). This demonstrates the importance of knee flexion angle and the effect it has on the ability of the hamstrings to combat the force created by the quadriceps. Greater hamstring stiffness has also been associated with lesser anterior tibial translation in 30 degrees of knee flexion suggesting that the hamstrings' ability to resist lengthening may also be an important factor in preventing anterior tibial translation and ACL injury (Blackburn, Norcross et al. 2011).

Flexion angles at the trunk, hip, and ankle have also been proposed to affect knee flexion angles (Blackburn and Padua 2008; Fong, Blackburn et al. 2011). A greater trunk flexion angle resulted in greater hip flexion and greater knee flexion during a drop landing task as compared to a lesser trunk flexion angle (Blackburn and Padua 2008). Greater passive dorsiflexion range of motion has been suggested to correlate with greater knee flexion angle during a drop landing task as well (Fong, Blackburn et al. 2011). This may be related to a more flexed landing posture which has been recommended as a prevention for ACL injury (Griffin, Agel et al. 2000). If flexion is increased at one joint in the lower extremity, some research propses that it may be increased at other joints, and this could be true of dorsiflexion range of motion as well (Blackburn and Padua 2008; Fong, Blackburn et al. 2011). More research in this area could result in a more clear understanding of how dorsiflexion range of motion plays a role in demonstrating a more flexed landing posture.

Implications for the Ankle

Biomechanical research has recently investigated ankle kinematics in relation to knee function suggesting lesser passive ankle dorsiflexion range of motion could negatively affect motion at the knee (Bell, Padua et al. 2008; Sigward, Ota et al. 2008). If the absorption of forces does not occur at the distal joint, the forces will be translated to the next joint, possibly causing increased forces and compensatory motion in that joint. Bell et al. (Bell, Padua et al. 2008) quantitatively assessed an overhead squat task to identify subjects that demonstrated medial knee displacement (MKD). Medial knee displacement was defined as the passing of the midpoint of the patella over the great toe during the overhead squat. When comparing the MKD group to controls, it was discovered that the MKD group displayed approximately 20% less dorsiflexion range of motion when measured passively with the knee bent. Furthermore, when the lack of dorsiflexion range of motion was corrected with a heel lift, subjects could complete the overhead squat without displaying MKD. This suggests that a lack of dorsiflexion range of motion could be directly related to MKD during an overhead squat. Sigward et al. (Sigward, Ota et al. 2008) analyzed a drop landing task in female soccer players ages 14-18 for frontal plane knee excursion after taking range of motion and strength measurements at the hip and ankle The results of this study also suggest lesser dorsiflexion range of motion may contribute to greater frontal plane knee excursion. This may also be due to the absorption of forces at the different joints through the kinetic chain. If less force is absorbed at the ankle, a greater force would have to be absorbed at the knee, making greater motion in the frontal plane necessary to absorb greater forces.

In contrast, studies have also proposed the opposite relationship with greater ankle dorsiflexion resulting in greater knee valgus. Zeller et al. (Zeller, McCrory et al. 2003) examined 9 male and 9 female subjects while performing a single leg squat. Maximum joint angles were recorded during the single leg squat with results suggesting women displayed greater knee valgus and reached greater dorsiflexion angles during the single leg squat. Kernozek et al. (Kernozek, Torry et al. 2005) performed a similar study analyzing a drop landing task. They measured peak ankle dorsiflexion during the task and discovered individuals that displayed greater frontal plane knee motion also displayed greater peak ankle dorsiflexion. Bell et al. and Sigward et al. obtained passive dorsiflexion range of motion measurements while Kernozek et al and Zeller et al. obtained peak dorsiflexion range of motion displayed while performing a task. The contrasting studies could be a result of the methodological differences in which dorsiflexion range of motion was assessed and the different tasks that were analyzed.

Factors Limiting Ankle Dorsiflexion

Previous ankle injury has been attributed to limited ankle dorsiflexion range of motion, and with studies demonstrating a reduction in talar glide after an ankle sprain, a limitation in ankle dorsiflexion could be attributed to a limitation in arthrokinematic motion (Wiesler, Hunter et al. 1996; Vicenzino, Branjerdporn et al. 2006). In order to achieve full dorsiflexion range of motion, the talus must roll anteriorly and simultaneously slide posteriorly (Neuman 2010). If this is motion is disrupted, dysfunction could occur. Posterior joint mobilizations have been applied to the talus to treat limited talar motion and results demonstrated an increase in dorsiflexion range of motion, suggesting that limitations in talar motion can affect ankle dorsiflexion range of motion (Green, Refshauge et al. 2001).

The gastrocnemius and soleus complex, or the triceps surae muscle group, has also been implicated as a cause for limited ankle dorsiflexion with studies demonstrating that stretching of these muscles increases ankle dorsiflexion range of motion (Peres, Draper et al. 2002). In a study by Condon et al. (Condon and Hutton 1987), stretching of the soleus was shown to increase ankle dorsiflexion range of motion. Isolated gastrocnemius tightness has also been implicated in individuals with a lack of ankle dorsiflexion range of motion (DiGiovanni, Kuo et al. 2002). These muscles, together or individually, can impact dorsiflexion range of motion along with talar motion. Through proper assessment, the etiology of limited ankle dorsiflexion can be identified and interventions can be applied to increase range of motion.

Areas of Needed Research

Ongoing research investigating the relationship between dorsiflexion range of motion, knee valgus angle, and knee flexion angle is necessary to build a more clear understanding of the relationship between these three factors. The analysis of two distinct groups, one with limited dorsiflexion range of motion and the other with normal dorsiflexion range of motion, may be helpful in identifying differences between the two groups. Different tasks could be utilized to determine whether differences between the groups occur during different types of movement such as a single leg squat, an overhead squat, and a jump landing task. A multifaceted approach to analyzing dorsiflexion range of motion may also contribute to the results of this study. Including passive dorsiflexion range of motion measured with the knee straight and knee bent, a functional measurement using the weight bearing lunge technique (Bennell, Talbot et al. 1998), arthrokinematic assessment, and dorsiflexion displacement during each task could contribute to the investigation of whether clinical measures of dorsiflexion range of motion correlate with the amount of dorsiflexion range of motion utilized during functional movements.

Summary

ACL injury is one of the most devastating injuries in sports. Injury mechanisms and risk factors need to be understood so prevention programs can be formulated to reduce the risk of injury. Risk factors at the hip and knee have been identified but limited research has been conducted on kinematics at the ankle and their effects on kinematics at the knee. A clear disagreement in the research exists with regards to dorsiflexion range of motion and this conflict needs to be addressed through further research. This study will compare individuals with a lack of dorsiflexion range of motion and those with normal dorsiflexion range of motion during three different tasks to determine differences in knee valgus angle, knee valgus displacement, medial knee displacement, knee flexion angle, knee flexion displacement, peak ankle dorsiflexion, and ankle dorsiflexion displacement. This study will also assess dorsiflexion range of motion using a variety of different techniques to determine if there is a correlation between different clinical measures of dorsiflexion range of motion and dorsiflexion range of motion utilized during a functional task. The design of this study will contribute to the current body of research and attempt to provide a more clear understanding of dorsiflexion range of motion, its effects on knee kinematics, and the relationship between different assessments of dorsiflexion range of motion.

Chapter III

Methodology

Subjects

Forty subjects (20 females, 20 males) participated in this study and were categorized into either the limited ankle dorsiflexion range of motion group (10 females, 10 males), or the normal dorsiflexion range of motion group (10 females, 10 males) based on a screening session. Subjects were recruited from The University of North-Carolina Chapel Hill and were between 18 and 25 years of age. Subjects were all qualified as physically active, defined as participating in 30 minutes of physical activity at least three times a week. Subjects were excluded from this study if they had a history of any lower extremity surgical procedure, lower extremity injury within the past six months that limited their physical activity for two days or more, or had a known neurological disorder. Before participating in this study each subject read and signed an informed consent form, completed a general medical history form, the Lysholm Knee Scoring Scale (Marx, Jones et al. 2001), and the Foot and Ankle Ability Measure (Martin, Irrgang et al. 2005), all approved by the University's Institutional Review Board.

Instrumentation

Dorsiflexion range of motion measurements were measured on the dominant limb of each subject in three positions; knee in complete extension (Figure 1) and the knee bent to 90 degrees (Figure 2) to incorporate both gastrocnemius and soleus flexibility (Piva, Fitzgerald et al. 2006), and weight bearing for a functional measurement. Measurements with the knee straight and the knee bent were taken with a standard 19” plastic goniometer in the supine position (Thoms and Rome 1997). Weight bearing dorsiflexion was measured using the weight bearing lunge technique described by Bennel et al. Reliability of this measure has been established (Bennell, Talbot et al. 1998) (Figure 3).

A/P talar glide was assessed using a portable instrumented ankle arthrometer (Blue Bay Research, Inc., Milton, FL) (Figure 4). The arthrometer consists of an adjustable plate that is fixed to the foot, a load-measuring handle that is attached to the footplate through which the load is applied, and a pad attached to the tibia. A six-degrees-of-freedom spatial kinematic linkage connects the tibial pad to the footplate that measures all components of motion of the footplate relative to the tibial pad (Kovaleski, Gurchiek et al. 1999; Kovaleski, Hollis et al. 2002; Hubbard, Kaminski et al. 2004). Measurements quantify the A/P load-displacement and Inv/Ev rotational laxity characteristics of the ankle-subtalar joint complex. During measurement, the force and torque loads produced via the arthrometer’s loading handle are transferred to the skeletal and soft tissue structures of the ankle-subtalar joint complex. The spatial kinematic linkage of the arthrometer measures the relative motion in millimeters between the arthrometer footplate and the reference pad attached onto the tibia (Hubbard, Kaminski et al. 2004).

Knee and ankle kinematics were captured using a Motion Star (Ascension Technologies Inc, Burlington, VA) electromagnetic tracking system. Knee and ankle kinematics in the frontal, sagittal, and transverse plane were collected at a sampling frequency of 140Hz. The electromagnetic sensors were placed over the midshaft of the second and third metatarsals of the foot, anteromedial aspect of the shank, lateral thigh, and sacrum. Global and segment axis systems were established with the *x*-axis designated as positive forward/anteriorly, the *y*- axis positive leftward/medially, and the *z*-axis positive upward/superiorly. The dominant limb was modeled by digitizing the hip, knee, and ankle joint centers. The knee joint center was defined as the midpoint between the digitized medial and lateral femoral condyles and the ankle joint center was defined as the midpoint between the medial and lateral malleoli. Left and right ASIS were digitized to determine the hip joint center of rotation using the Bell method.(Bell, Pedersen et al. 1990). The Motion Monitor v8.0 (Innovative Sports Training, Chicago, IL, USA) was used for model generation/calibration and data acquisition. A non-conductive force plate (Bertec Corp., Columbus, OH, USA) was used to collect kinetic data sampled at 1400Hz to determine initial contact during the jump landing task.

Testing Procedures

Subjects were placed in groups through a screening process that identified subjects with limited dorsiflexion range of motion defined by ($\leq 5^{o}$), and subjects with normal dorsiflexion range of motion ($\geq 15^{o}$) passively measured with the knee straight (Moseley, Crosbie et al. 2001). All measurements were taken in the supine position on the dominant limb defined by the limb used to kick a ball for maximum distance. Subjects read and signed an informed consent form (Appendix 3) before participating in the screening process. Once subjects had been assigned to groups, they reported to the Sports Medicine Research Laboratory for a single testing session that lasted approximately one and a half hours. Upon arrival, subjects completed a general medical health questionnaire (Appendix 4), Lysholm Knee Scoring Scale (Appendix 5), and the Foot and Ankle Ability Measure (Appendix 6) all approved by the University's Institutional Review Board. Height and mass were recorded for each subject and they completed a five minute upper body cardiovascular warm-up on a stationary bike at moderate intensity determined by a rate of perceived exertion of 3 out of 10. Dorsiflexion range of motion was then be measured by all three techniques in a counterbalanced order (Table 1 & 2); supine with the knee straight, supine with the knee bent to 90 degrees, and using the weight bearing lunge technique (WBLT) (Bennell, Talbot et al. 1998). A/P talar glide was measured in a counterbalanced order with the passive dorsiflexion measurements. The ankle dorsiflexion angle was measured using a goniometer as the angle formed by the shaft of the fibula and the lateral midline of the foot (Piva, Fitzgerald et al. 2006). To perform the weight bearing lunge measurement, subjects placed their foot perpendicular to the wall and lunge forward to touch the wall with their knee. The foot was then moved posteriorly until the maximum range of dorsiflexion is reached, which was identified by the heel lifting off the ground. The distance from the great toe to the wall as then be measured in centimeters with a tape measure and a gravity inclinometer was attached distal to the tibial tuberosity to measure the angle of the tibia relative to the vertical (Bennell, Talbot et al. 1998). Each of the measures for dorsiflexion range of motion was taken three times and the arithmetic mean was recorded and used for data analysis.

After range of motion measurements were recorded, the subject was prepared for motion analysis data collection. Tracking sensors were placed over the midshaft of the second and third metatarsals of the foot, the anteromedial aspect of the shank, lateral thigh, and sacrum. Markers were placed on the skin with double-sided tape and secured with pre-wrap and athletic tape. The shoe was unlaced and the tongue was pulled forward and fastened to the top of the shoe with double-sided tape to expose the dorsum of the foot and allow sensor placement. The shoe was then re-laced to ensure proper fit. The participants did not wear socks so the sensor could be firmly attached to the skin. This procedure was performed to allow space for the sensor on the foot while the subject could still wear their athletic shoes while performing the jump landing task. The shoes were removed for the SLS and OHS without disrupting the sensor placement to allow for barefoot completion of these two tasks. Global and segment axis systems were established with the X-axis designated as positive anteriorly, the Y-axis positive to the left of each subject, and the Z-axis positive superiorly. Each subject completed an overhead squat, single leg squat, and a jump landing task in a counterbalanced order (Table 3 & 4). The overhead squat task was performed with the feet shoulder width apart, arms raised vertically overhead, heels on the ground, squatting to at least 60 degrees of knee flexion (Figure 5). The single leg squat was performed with the hands on the hips, and again, squatting to at least 60 degrees. The opposite leg was raised in front of the subject with the foot approximately 10 cm off the ground (Figure 6). A metronome set at 60 bpm was used to ensure the cadence of each squatting task for each subject was similar. The jump landing task consisted of subjects jumping from a 30 cm box placed a distance of 50% of their standing height away from the force plate, landing on the force plate, and immediately jumping as high as possible. Subjects did not jump vertically but horizontally, onto the force place (Padua, Marshall et al. 2009) (Figure 7). Subjects were verbally instructed on how to complete each task and were allotted up to five practice trials of each task before data were collected. A two minute rest period was allotted between the practice trials and data collection. Each subject performed five consecutive trials of the overhead squat and single leg squat with a one minute rest period between each task.

Subjects performed five separate repetitions of the jump landing task with a thirty second rest period between each trial.

Data Processing and Reduction

Three-dimensional coordinates of lower extremity bony landmarks were estimated using Motion Monitor Software (Innovative Sports Training, Chicago, IL). An embedded right-handed Cartesian coordinate system was defined for the foot, shank, thigh, and pelvis segments to describe the three-dimensional position and orientation of these segments. All kinematic data were smoothed with a Butterworth (fourth-order, zero-phase lag) low-pass digital filter at 14.5 Hz. Kinematic and kinetic data was reduced using custom Matlab software (Mathworks, Natick, MA). Joint angles were calculated using an Euler angle sequence, rotating in an order of (1) flexion-extension (y-axis), (2) valgus-varus (x-axis), and (3) internal-external rotation (z-axis). Data was analyzed during the descent phase of each task, defined as the initiation of movement to peak knee flexion for the squat tasks and initial ground contact (VGRF > 10N) to peak knee flexion for the jump-landing task. Joint displacements calculated during the descent phases were used for further analysis. Joint angles were calculated using an Euler angle sequence, rotating in an order of flexion(+)-extension(-) (Y-axis), and valgus(-)–varus(+) (X-axis), and internal(+)-external(-) rotation (Z-axis). Data was analyzed during the decent phase of each task. Peak knee flexion angle was defined as the maximum knee flexion angle achieved during each task. Knee flexion displacement was defined as the angle of knee flexion at initial ground contact subtracted from the peak knee flexion angle reached during the descent phase of the jump landing task. Peak knee valgus angle was defined as the peak knee valgus angle observed during each task. Knee valgus displacement was calculated by subtracting the initial knee valgus angle from the peak knee valgus angle reached during each task. Medial knee displacement was defined as the total straight-line medial displacement of the joint center along the y-axis during the descent phase of each task. This was calculated in centimeters from initial point of the knee joint center to the maximum medial placement of the knee joint center during each task. Ankle dorsiflexion displacement was defined as the total dorsiflexion range of motion utilized at the ankle during each task. The averages of the peak values of 3 trials were calculated for each kinematic variable.

Statistical Analysis

All statistical analyses were performed using SPSS Software Version 19.0 (SPSS Inc. Chicago, IL). Separate between subjects ANOVAs were performed to determine differences in peak knee flexion, knee flexion displacement, peak knee valgus angles, knee valgus displacement, medial knee displacement, and ankle dorsiflexion displacement between the two groups during each task. Pearson's product-moment coefficients were calculated between ankle joint displacement and ankle dorsiflexion range of motion values during the dorsiflexion measures to determine if there was a relationship between talar motion in the A/P direction, ankle dorsiflexion measured with the knee straight, knee bent to 90º, using the weight bearing lunge technique, and peak dorsiflexion reached during each task. A priori alpha level was set at .05.

Chapter IV

Manuscript

INTRODUCTION

Approximately 80,000-250,000 ACL injuries occur in the United States annually, with the majority of these injuries occurring in individuals ages 15 to 25 who participate in sports (Griffin, Agel et al. 2000; Griffin, Albohm et al. 2006). In addition to these concerning numbers, 70% of ACL injuries result from non-contact mechanisms, defined as no contact with another player or piece of equipment, such as plant-and-cut maneuvers, landing from a jump, and decelerating (Boden, Griffin et al. 2000; Hewett, Myer et al. 2006). The high incidence of non-contact injury is driving ongoing research toward investigating possible biomechanical and neuromuscular variables that could contribute to non-contact ACL injury mechanisms.

Knee position during lower extremity movement can greatly impact the load placed on the ACL. Both cadaveric (Withrow, Huston et al. 2006; Oh, Lipps et al. 2012) and in-vivo (Beynnon, Johnson et al. 1997) research protocols have demonstrated that greater knee valgus, greater tibial internal rotation, and decreased knee flexion angles during movement place greater strain on the ACL. Withrow et al. (Withrow, Huston et al. 2006) reported a 30% increase in ACL strain with an impulsive knee valgus moment during a simulated jump landing. Greater ACL strain was observed in-vivo when the knee was in a less flexed position during both a double leg squat and knee flexion-extension exercises (Beynnon, Fleming et al. 1995; Beynnon, Johnson et al. 1997). Therefore, understanding what factors are associated with knee positions that increase ACL loading may improve our knowledge of ACL injury mechanisms and facilitate injury prevention efforts.

Dynamic tasks such as the overhead squat (Bell, Padua et al. 2008), single leg squat (Willson, Ireland et al. 2006)and jump-landings (Padua, Marshall et al. 2009) have been used in laboratory and clinical settings to elucidate faulty lower extremity movement patterns and identify individuals potentially at risk for injury. More recently, available range of motion at the ankle has been considered as a potential influence on knee movement during dynamic tasks and subsequent injury risk (Piva, Goodnite et al. 2005). However, the relationship remains elusive. Some studies have observed less ankle dorsiflexion range of motion is associated with greater medial knee displacement (Bell, Padua et al. 2008; Sigward, Ota et al. 2008). Bell, Padua et al. (Bell, Padua et al. 2008) studied individuals with medial knee displacement, which is a clinical observation of dynamic valgus collapse, and observed that subjects displaying medial knee displacement during an overhead squat had approximately 20% less passive dorsiflexion in comparison to subjects who did not display medial knee displacement. Furthermore, the medial knee displacement observed during the overhead squat was corrected when a lift was placed under the heel. Potentially, this may have occurred due to the increased dorsiflexion range of motion that the subjects could utilize when they had the assistance of the heel lift. In addition, less dorsiflexion range of motion has been associated with greater frontal plane knee excursion during a drop landing in young female soccer players (Sigward, Ota et al. 2008) and with a decreased knee flexion angle during a jump landing task (Fong, Blackburn et al. 2011). In contrast, results from two studies suggest that females with greater knee valgus during a single-leg squat and drop landing displayed greater dorsiflexion range of motion measured during each task (Zeller, McCrory et al. 2003; Kernozek, Torry et al. 2005). This body of research suggests that ankle dorsiflexion range of motion may contribute to the amount of knee valgus and knee flexion an individual utilizes during dynamic movement, but the relationship is unclear.

The conflicting results in previous research may be due to the different techniques used to assess dorsiflexion range of motion and possibly the tasks utilized. Some researchers assessed passive dorsiflexion range of motion prior to the performance of their various tasks (Bell, Padua et al. 2008; Sigward, Ota et al. 2008), while others assessed peak dorsiflexion angles achieved during the tasks performed (Zeller, McCrory et al. 2003; Kernozek, Torry et al. 2005). The contrast in the results may be due to the inability of a passive dorsiflexion range of motion measurement to accurately determine the amount of dorsiflexion an individual uses during a functional task. Perhaps, a weight bearing measurement may be a better assessment of dorsiflexion range of motion to indicate motion used during a functional task. For this reason, passive range of motion and weight bearing range of motion were both measured in the current study and used separately to stratify subjects into normal and limited categories for analysis.

The purpose of the current study was to investigate knee and ankle kinematics during dynamic tasks in subjects that were identified as having limited dorsiflexion range of motion in comparison to subjects with normal dorsiflexion range of motion. Ankle dorsiflexion motion was assessed passively through both weight bearing and non-weight bearing techniques prior to testing and total displacement during dynamic movement was also calculated. The goal of comparing a limited and normal group was to more clearly describe the relationship between dorsiflexion range of motion and knee kinematics, potentially identifying a range of motion assessment that could be used clinically to indicate how an individual will perform during a more functional task. We hypothesized that individuals with less dorsiflexion range of motion, both non-weight bearing and weight bearing, would display kinematics associated with ACL loading (less sagittal plane motion and greater frontal plane motion) during an overhead squat, single leg squat, and jump landing task.

METHODS

Subjects

Potential subjects were screened using a non-weight bearing measure of passive dorsiflexion (DF) range of motion, with the knee straight (Figure 1), as an initial means of identifying participants with normal (≥15°) or limited (≤ 5°) motion. This screening assessment was chosen based on previous literature (Moseley, Crosbie et al. 2001) and as a method commonly used in the clinic. This allowed us to create groups with different and non-overlapping passive DF range of motion. Forty physically active subjects, 20 males and 20 females were identified through screening that met the criteria and volunteered to participate in this study. In total 10 males and 10 females were identified for both the normal (NORM) and limited (LIM) motion groups, group demographics are depicted in Table 5. Physically active was defined as 30 minutes of moderate physical activity at least three times per week. Subjects were excluded from this study if they had a passive DF range of motion measurement between six and 14 degrees, a history of any lower extremity surgical procedure, lower extremity injury within the past six months that limited their physical activity for two or more days, or had a known neurological disorder. Before participating in this study each subject read and signed an informed consent form (Appendix 3) approved by the University's Institutional Review Board and completed a general medical history in order to verify inclusion criteria (Appendix 4).

Instrumentation

Dorsiflexion range of motion measurements were performed on the dominant kicking limb of each subject using three methods; passive DF with the knee fully extended (Figure 1), passive DF with the knee flexed to 90 degrees (Figure 2) to incorporate both gastrocnemius and soleus flexibility (Piva, Fitzgerald et al. 2006), and using a weight bearing lunge technique (WBLT) (Figure 3). Dorsiflexion range of motion measurements with the knee straight and the knee bent were taken with a standard 19" plastic goniometer in the supine position (Thoms and Rome 1997). Ankle dorsiflexion during the WBLT was measured using a digital inclinometer (The Saunders Group, Chaska, MN) (Bennell, Talbot et al. 1998).

Knee and ankle kinematics were captured using an electromagnetic motion tracking system (Motion Star, Ascension Technologies Inc, Burlington, VA). Knee and ankle kinematics in the frontal, sagittal, and transverse planes were collected at a sampling frequency of 140Hz. All kinematic and kinetic data were processed using Motion Monitor Software (Innovative Sports Training Inc, Chicago, Illinois) and exported into a customized software program (MatLab 11, MathWorks, Natick, Massachusetts) for data reduction. A non-conductive force plate (Bertec Corp., Columbus, OH, USA) was used to collect kinetic data sampled at 1400Hz to determine initial contact during the jump landing task.

Testing Procedures

Once subjects had been identified and designated to a group through the initial screening, they reported to the Sports Medicine Research Laboratory for a single testing session that lasted approximately one and a half hours. Height and mass were recorded for each subject and they completed a five-minute upper body cardiovascular warm-up on a stationary bike at moderate intensity determined by a rate of perceived exertion of 3 out of 10. An upper body warm-up was chosen so that the range of motion assessments would not be influenced by pedaling a bike with the lower extremities.

For testing, each subject was assessed on all three techniques in a randomized order; supine with the knee straight, supine with the knee bent to 90 degrees, and the WBLT. The ankle dorsiflexion angle for the non-weight bearing assessments was measured as the angle formed by the shaft of the fibula and the lateral midline of the foot (Piva, Fitzgerald et al. 2006). To perform the WBLT, subjects placed their foot perpendicular to the wall and lunged forward to touch the wall with their knee. The foot was then moved posteriorly until the maximum range of dorsiflexion was reached, which was identified by the heel lifting off the ground. A digital inclinometer was placed distal to the tibial tuberosity to measure the angle of the tibia relative to the vertical (Bennell, Talbot et al. 1998) (Figure 3). Each of the measures for dorsiflexion range of motion were taken three times and the arithmetic mean was recorded and used for data analysis.

After range of motion measurements were recorded, the subject was prepared for motion analysis data collection. Electromagnetic tracking sensors were placed on the skin with double-sided tape and secured with pre-wrap and athletic tape. The sensors were placed over the midshaft of the second/third metatarsals of the foot, anteromedial aspect of the proximal tibia, lateral aspect of the thigh, and the spinous process of L5. The shoe was unlaced and the tongue was pulled forward and fastened to the top of the shoe with double-sided tape to expose the dorsum of the foot and allow sensor placement. The shoe was then re-laced to ensure proper fit (DiStefano, Padua et al. 2008). The participants did not wear socks so the sensor could be firmly attached to the skin. This procedure was performed to allow space for the sensor on the foot while the subject could still wear their athletic shoes to perform the jump landing task. The shoes were removed for the SLS and OHS without disrupting the sensor placement to allow for barefoot completion of these two tasks. Data indicating the orientation and position of each sensor relative to a standard range transmitter were conveyed back to a personal computer. The dominant limb was modeled by digitizing 6 additional landmarks to define the hip, knee, and ankle joint centers. The knee joint center was defined as the midpoint between the digitized medial and lateral femoral condyles and the ankle joint center was defined as the midpoint between the medial and lateral malleoli. Left and right ASIS were digitized to determine the hip joint center of rotation using the Bell method.(Bell, Pedersen et al. 1990). Global and segment axis systems were established with the X-axis designated as positive in the anterior direction from the subject, the Y- axis positive to the left, and the Z-axis positive in the upward direction.

Each subject completed an overhead squat, single leg squat, and a jump landing task in a randomized order. The overhead squat task was performed with the feet shoulder width apart, arms raised vertically overhead, heels on the ground, squatting to at least 60 degrees of knee flexion (Bell, Padua et al. 2008) (Figure 5). The single leg squat was performed with the hands on the hips, opposite leg raised in front of the subject with the foot approximately 10 cm off the ground, squatting to at least 60 degrees of knee flexion (Willson, Ireland et al.

2006) (Figure 6). A metronome set at 60 bpm was used to ensure the cadence of each squatting task for each subject was similar and the degree of knee flexion was assessed in real time using motion monitor software. The jump landing task consisted of subjects jumping from a 30cm box placed at a distance of 50% of their standing height away from the force plate, landing on the force plate, and immediately jumping as high as possible. Subjects did not jump vertically but horizontally, onto the force place (Padua, Marshall et al. 2009) (Figure 7). Subjects were verbally instructed on how to complete each task and were allotted up to five practice trials of each task before data were collected. A one minute rest period was allotted between the practice trials and data collection. Each subject performed five consecutive trials of the overhead squat and single leg squat with a one minute rest period between each task. Subjects performed five separate repetitions of the jump landing task with a thirty second rest period between each trial.

Data Reduction and Analysis

Three-dimensional coordinates of lower extremity bony landmarks were estimated using Motion Monitor Software (Innovative Sports Training, Chicago, IL). An embedded right-handed Cartesian coordinate system was defined for the foot, shank, thigh, and pelvis segments to describe the three-dimensional position and orientation of these segments. All kinematic data were smoothed with a Butterworth (fourth-order, zero-phase lag) low-pass digital filter at 14.5 Hz. Kinematic and kinetic data was reduced using custom Matlab software (Mathworks, Natick, MA). Three-dimensional knee and ankle joint angles were calculated using an Euler angle sequence, rotating in an order of (1) flexion-extension (*y*-axis), (2) valgus-varus (*x*-axis), and (3) internal-external rotation (*z*-axis). Data was analyzed during the descent phase of each task, defined as the initiation of movement to peak knee flexion for the squat tasks and initial ground contact (VGRF > 10N) to peak knee flexion for the jump-landing task. Joint displacements calculated during the descent phases were used for further analysis. Knee flexion displacement, knee valgus-varus displacements, knee internal-external rotation displacements, and ankle dorsiflexion displacement were calculated by subtracting the angle at the time point of initiation of movement (squats) or initial ground contact (jump landing) from the peak angle reached during the descent phase of each task. The average of the peak values across 3-trials was calculated for each of kinematic variables.

Statistical Analysis

Three separate one-way ANOVAs, one for each task, were performed to analyze group differences (NORM = 20; LIM =20) in knee and ankle kinematics based on group assignment using the dorsiflexion (DF) range of motion with the knee straight measurement. Bivariate Pearson product moment correlation analyses were performed to determine the relationship between the three different ankle DF range of motion measures. Moderate correlations were observed between the three different ankle DF range of motion measurements (Table 6). As such, some individuals who were classified as being limited in DF range of motion during the knee straight ankle DF range of motion assessment had similar values on knee bent ankle DF range of motion assessment or WBLT measures as those individuals in the normal DF range of motion group. To ensure we compared subjects who had different and non-overlapping DF range of motion on each ankle DF range of motion assessment we determined the tertile cutpoints for the knee bent ankle DF range of motion and WBLT measures. This allowed us to create three distinctive groups based on both their knee bent and WBLT measures. The LIM group for the knee bent and WBLT measures were those subjects in the lower tertile (n=13). The NORM group for the knee bent and WBLT measures were those in the upper tertile (n=13). Group comparisons (NORM = 13; LIM =13) of knee and ankle kinematics based on knee bent ankle DF range of motion and WBLT group assignment were also made using separate one-way ANOVAs. A priori alpha level was set at $p = .05$ for all analyses. All statistical analyses were performed using SPSS Software Version 19.0 (SPSS Inc. Chicago, IL).

RESULTS

Intra class correlation coefficients were calculated to determine intra-rater reliability for the range of motion assessments. The results were strong for both the passive dorsiflexion measurement with the knee straight (ICC (3,k)= 0.988, SEM= 0.88º), knee bent (ICC (3,k)= 0.898, SEM= 2.58º), the WBLT cm (ICC (3,k)= 0.972, SEM= 0.41cm), and WBLT angle (ICC (3,k)= .953, SEM= 1.61º). The results of all range of motion assessments by groups are displayed in Table 7.

Knee Straight Ankle ROM Based Group Comparisons

No significant group (NORM, LIM) differences were observed in knee and ankle displacements during any of the tasks when compared based on ankle ROM with the knee straight. Thus, based on these findings, individuals who demonstrate differences in ankle DF range of motion with the knee straight do not demonstrate differences in sagittal plane displacement at the ankle or knee, as well as no difference in frontal plane knee motion. Results of these analyses are presented in Table 8.

Knee Bent Ankle ROM Based Group Comparisons

During the overhead squat, the NORM group (ankle DF range of motion ≥ 20.44°) displayed significantly greater knee flexion displacement ($F_{(1,24)} = 9.48$, $P < .001$, NORM = 104.61 ± 13.37, LIM = 87.79 ± 14.46) and ankle DF displacement ($F_{(1,24)} = 10.24$, $P = .004$, NORM = -33.25 ± 6.45, LIM = -25.69 ± 5.45) compared to the LIM group (ankle DF range of motion ≤ 9.67°). Similarly, during the single leg squat, individuals in the NORM group displayed significantly greater knee flexion displacement ($F_{(1,24)}$ = 5.94, *P* = .023; NORM = 76.30 ± 10.10, LIM = 65.83 ± 11.73) and ankle DF displacement ($F_{(1,24)}$ = 6.51, *P* = .018, NORM = -31.39 ± 5.58, LIM = -25.37 ± 6.41). While not significant, knee external rotation displacement was trending toward significance during the jump landing task indicating those with greater DF range of motion with the knee bent could potentially go through a greater amount of knee external rotation displacement during a jump landing ($F_{(1,24)}$ = 4.04, *P* = .056, NORM = -3.54 ± 4.99, LIM = -0.65 ± 1.42) (Table 9).

WBLT Based Group Comparisons

During the overhead squat, the NORM group (WBLT ≥ 47.44°) displayed significantly greater knee flexion displacement ($F_{1,24}$=18.79, p<0.001) and ankle DF displacement ($F_{1,24}$=30.62, p<0.001) in comparison to the LIM group (WBLT ≤ 41.22°) . Similarly, during the single leg squat, individuals with greater DF during the WBLT displayed significantly greater knee flexion displacement ($F_{1,24}$=20.67, p<0.001) and ankle DF displacement ($F_{1,24}$=18.83, p<0.001) and also greater knee varus displacement ($F_{1,24}$=4.92, p=0.036). There were no significant WBLT group differences during the jump landing task (Table 10).

The effect sizes for all significant findings are displayed in Table 11.

DISCUSSION

Our most important findings were that grouping individuals based on a non-weight bearing assessment of passive ankle range of motion with the knee straight was not indicative of lower extremity kinematics during our selected tasks. We found that this original grouping method was not effective in clearly separating the subjects based on range of motion on all of our assessments. For instance, subjects categorized as limited (≤ 5° DF) on the passive DF with knee straight assessment could be normal on the WBLT (≥ 47.44°). However, we did observe group differences in lower extremity kinematics when re-categorizing the same subjects based on the WBLT and passive DF with the knee bent. Specifically, those with lesser ankle DF during the weight bearing lunge and knee bent measurements had less knee flexion displacement and ankle DF displacement during the squatting tasks. Individuals with greater range of motion according to the WBLT showed greater knee varus displacement during the SLS and subjects with greater range of motion according to the knee bent measurement had greater external rotation displacement during the JL. Generally, the results do support our hypothesis in that restricted motion at the ankle does affect lower extremity movement at the knee and ankle. However, based on previous research we were surprised to find there were no group differences in our initial analysis. For clarity of presentation, our discussion will be organized based on ankle range of motion assessments.

Passive DF with Knee Straight

Our finding that subjects in the LIM and NORM groups for passive DF range of motion with the knee straight actually had similar three-dimensional kinematics during movement is both similar and dissimilar to previous research. Fong et al. (Fong, Blackburn et al. 2011) observed greater DF range of motion assessed passively with the knee straight was associated with greater knee flexion during landing. However, similar to our study, DF was not associated with knee frontal plane movement. A possible explanation for the contradiction in results is the differences in the jump landing task used. We had subjects perform a landing from a 30-cm box at a distance of 50% of their standing height from the force place with an immediate countermovement into a maximal vertical jump. Fong et al. (Fong, Blackburn et al. 2011) had subjects jump forward from a similar height box at a distance of 40% of their standing height. They did not incorporate a maximal vertical jump after landing as they were attempting to isolate the biomechanical control of the loading phase in association with ankle movement. Our subjects were preparing for a quick vertical jump so perhaps they did not utilize greater knee flexion even if they were capable simply because of our task.

Passive DF with Knee Bent

Greater ankle DF with the knee bent contributed to greater knee flexion displacement and ankle DF displacement during the squatting tasks in our study. Our findings agree with previous work that observed subjects with excessive medial knee displacement or excursion during squatting or landing tasks also had limited motion at the ankle when assessed passively with the knee bent (Bell, Padua et al. 2008; Sigward, Ota et al. 2008). In addition, their passive DF assessments with the knee straight were not associated with frontal plane knee movement.

In our study, individuals with greater DF range of motion with the knee bent were trending towards demonstrating greater knee external rotation displacement during the jump landing task. This was the only movement close to significance for this particular task, regardless of how subjects were grouped. In an attempt to explain these results, we looked at knee position at the time point of initial contact, which was identified to calculate displacements during the jump landing. There were no differences between groups on any of the variables at initial contact. However, the normal group went on to use relatively more knee external rotation during the descent phase. Knee flexion displacement did not differ on this task, but the same individuals utilized greater knee flexion displacement during both squatting tasks. Perhaps they were capable of utilizing greater knee flexion during the jump landing but it was not necessary with the quick countermovement vertical jump. It is plausible to think that the greater sagittal plane motion an individual is able to use will allow them to adopt some movement at the knee in other planes of motion. Knee internal and external rotation have been associated with ACL injury risk in previous literature (Olsen, Myklebust et al. 2004). However, cadaveric studies have suggested that tibial external rotation decreases ACL strain in positions of knee flexion and in contrast, tibial internal rotation places greater strain on the ACL (Markolf, Burchfield et al. 1995). This may suggest that the individuals that had increased external rotation displacement may be moving out of a position of relative “danger”.

Weight Bearing Lunge Technique

Greater DF during the WBLT contributed to greater sagittal plane displacement at the knee and ankle during the squatting tasks. Our findings are consistent with Macrum et al. (Macrum, Bell et al. 2011) who found individuals with lesser ankle DF displacement displayed lesser knee flexion during a squatting task. In this study, they placed a wedge under the subject’s feet to increase the DF angle with which the subjects started. This decreased the amount of DF displacement the individual could use and resulted in lesser knee flexion displacement. This suggests that individuals with greater DF use greater DF displacement and knee flexion displacement during squatting tasks.

We also found that greater DF during the WBLT contributed to greater knee varus displacement during the single leg squat. This finding is in agreement with Sigward et al. (Sigward, Ota et al. 2008) who found greater frontal plane knee motion in individuals with lesser DF range of motion. It is well documented that knee valgus loading is a risk factor for potential ACL injury (Griffin, Albohm et al. 2006). However, knee osteoarthritis (OA) literature clearly states that knee varus positioning is deleterious for the medial knee compartment and the future onset of knee OA and other potential injuries (Roos 2005). Therefore, it seems frontal plane knee movement in either direction is not favorable. The greater knee varus displacement in the same individuals who had greater knee flexion displacement may simply be due to the greater overall sagittal plane motion during the single leg squat, which allows them more time to go through a varus displacement.

The results of this study suggest individuals with greater DF range of motion measured with the WBLT and passive with the knee bent display greater knee flexion displacement and ankle DF displacement. The clinical importance of these findings is magnified by the effect sizes associated with these differences. The difference in knee flexion displacements has an average of approximately 20 degrees during the OHS and approximately 15 degrees during the SLS which are clinically relevant differences. Lesser knee flexion angles have been shown to increase the load placed on the ACL (Beynnon, Fleming et al. 1995; Beynnon, Johnson et al. 1997), primarily due to the increase in quadriceps muscle contraction (Durselen, Claes et al. 1995; DeMorat, Weinhold et al. 2004; Withrow, Huston et al. 2006), which contributes to anterior tibial translation. The resultant anterior tibial translation places a shear force on the ACL (Beynnon, Fleming et al. 1995), which can lead to injury. Larger knee flexion angles may decrease activation of the quadriceps resulting in less strain on the ACL (Blackburn and Padua 2009). Therefore, it would be beneficial to utilize a greater amount of knee flexion during athletic tasks to decrease strain on the ACL.

Based on our study results, assessing dorsiflexion range of motion in both weight bearing and non-weight bearing may be beneficial when evaluating lower extremity movement. The WBLT measurements showed a moderate-strong correlation with ankle DF displacements. This suggests that the WBLT may be a more functional assessment which could be the case because it is weight bearing. A weight bearing measurement requires more torque to be placed on the ankle when the measurement is taken, which may force the individual to reach maximum DF during the measurement. It also requires a similar motion to the squatting tasks that were used in this study. We also notice with the WBLT that the angle of the tibia had the strongest correlation with ankle DF displacement. This may be due to the fact that the centimeter measurement does not account for the length of the tibia or foot. Anthropometrics can therefore alter the specificity of the centimeter measurement however they do not affect the angle of the tibia.

We also observed that the knee bent measurement had a higher correlation with ankle DF displacements than did the knee straight measurement. This may be due to the fact that functional movement does not occur with the knee straight but with the knee bent. These results might suggest that a measurement with the knee bent is more functional. Both passive and weight bearing measurements of dorsiflexion seem to be important when we are evaluating DF range of motion. An individual could be limited when using one measurement but not limited when using another. This can be explained by the difference in each of the measurements. The knee straight measurement assesses the extensibility of the gastrocnemius while the knee bent measurement assesses the extensibility of the soleus (Piva, Fitzgerald et al. 2006). The WBLT is performed in a weight bearing position therefore requiring more torque on the ankle and including both muscular and arthrokinematic motion. Based on these findings, we suggest a battery of assessments as one individual may appear normal on one technique, but may have severe restrictions on another. The advantage of understanding this relationship further is that ankle dorsiflexion restrictions are modifiable (Mahieu, Witvrouw et al. 2006) and may serve as a means to decrease knee injury rates, especially ACL injury.

Limitations

This study is not without limitations. The investigators were not blinded to the subjects' group assignment, which may have caused unintentional bias during range of motion measurements. We also used specific criteria to assign groups so the results may only be applicable to individuals who meet those criteria and may not be applicable to the general population. We did not assess muscle activation or strength during this study and both are shown to affect kinematics at the knee. Further research should include this assessment along with range of motion to help determine their relationship on knee and ankle kinematics.

Recommendations for Further Research

Future research should continue to study the relationship between dorsiflexion range of motion and knee kinematics. The overall picture is still unclear with conflicting results. Perhaps establishing a valid and efficient clinical measurement to represent functional dorsiflexion range of motion may allow us to help predict knee and ankle kinematics, thus helping identify individuals at risk for injury. This identification could lead to intervention programs that may help decrease ACL injury risk.

Appendix 1

Tables

Table 1. Dorsiflexion Range of Motion Measurement Counterbalanced Order (Limited Group)

Subject 1	Knee Straight, Knee Bent, WBLT
Subject 2	Knee Straight, WBLT, Knee Bent
Subject 3	WBLT, Knee Straight, Knee Bent
Subject 4	WBLT, Knee Bent, Knee Straight
Subject 5	Knee Bent, WBLT, Knee Straight
Subject 6	Knee Bent, Knee Straight, WBLT

* This order was repeated after the 6^{th} subject

Table 2. Dorsiflexion Range of Motion Measurement Counterbalanced Order (Normal Group)

Subject 1	Knee Straight, Knee Bent, WBLT
Subject 2	Knee Straight, WBLT, Knee Bent
Subject 3	WBLT, Knee Straight, Knee Bent
Subject 4	WBLT, Knee Bent, Knee Straight
Subject 5	Knee Bent, WBLT, Knee Straight
Subject 6	Knee Bent, Knee Straight, WBLT

* This order was repeated after the 6^{th} subject

Table 3. Limited Group Counterbalanced Testing Order

Subject 1	OHS, SLS, JL
Subject 2	OHS, JL, SLS
Subject 3	SLS, OHS, JL
Subject 4	SLS, JL, OHS
Subject 5	JL, SLS, OHS
Subject 6	JL, OHS, SLS

*This order was repeated after the 6^{th} subject

Table 4. Normal Group Counterbalanced Testing Order

Subject 1	OHS, SLS, JL
Subject 2	OHS, JL, SLS
Subject 3	SLS, OHS, JL
Subject 4	SLS, JL, OHS
Subject 5	JL, SLS, OHS
Subject 6	JL, OHS, SLS

*This order will be repeated after the 6^{th} subject

Table 5. Group Characteristics (Means ± SD)

	Based on DF ROM (Knee Straight)		Based on DF ROM (Knee Bent)		Based on WBLT	
	Normal (n=20)	**Limited (n=20)**	**Normal (n=13)**	**Limited (n=13)**	**Normal (n=13)**	**Limited (n=13)**
Age (years)	20.70 ± 1.98	19.45 ± 1.40	21.38 ± 1.85	19.38 ± 1.56	19.54 ± 1.39	21.31 ± 1.84
Height (cm)	172.33 ± 9.73	171.12 ± 8.64	171.78 ± 9.50	172.37 ± 8.62	173.58 ± 9.29	169.82 ± 10.49
Mass (kg)	70.13 ± 13.80	70.42 ± 12.50	70.65 ± 16.83	71.66 ± 13.65	73.58 ± 13.87	65.86 ±16.07

Table 6. Bivariate Linear Correlation Results

Ankle DF DSP	**WBLT cm** r-value	**WBLT Angle** r-value	**DF knee Straight** r-value	**DF Knee Bent** r-value
OHS	*-0.653	* -0.731	-0.298	*-0.396
SLS	*-0.538	*-0.636	-0.313	*-0.452
JL	*0.241	*0.199	0.007	-0.069

Table 7. Ankle Dorsiflexion Range of Motion (degrees) for each Assessment by Group (Mean ± SD)

	Based on DF ROM (Knee Straight)		**Based on DF ROM (Knee Bent)**		**Based on WBLT**	
	Normal (n=20)	**Limited (n=20)**	**Normal (n=13)**	**Limited (n=13)**	**Normal (n=13)**	**Limited (n=13)**
DF Straight	16.78 ± 2.16	1.63 ± 2.58	17.23 ± 2.43	0.85 ± 2.75	14.97 ± 5.91	5.41 ± 7.52
DF Bent	22.27 ± 4.50	8.52 ± 3.76	24.23 ± 4.28	6.44 ± 2.53	22.59 ± 7.03	11.23 ± 6.25
WBLT	48.35 ± 7.61	41.30 ± 5.37	52.13 ± 6.63	40.61 ± 52.13	53.52 ± 4.38	36.82 ± 2.30

Table 8. Group Comparisons of Knee and Ankle Kinematics (Means ± SD) for the Normal and Limited DF range of motion groups for each task (OHS, SLS, JL) with 95% Confidence Intervals (CI).

DSP	Overhead Squat		Single Leg Squat		Jump Landing	
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
Knee Flex						
Normal	100.38 ± 13.73	(93.68, 107.08)	75.58 ± 11.00	(67.02, 78.13)	76.14±14.72	(69.59, 82.70)
Limited	92.56 ± 15.79	(85.87, 99.26)	67.74 ±13.42	(62.20, 73.30)	74.38±14.23	(67.83, 80.93)
Knee Vlg						
Normal	-2.36 ± 3.86	(-3.72, -1.00)	-2.44 ±2.74	(-3.38, -1.50)	-1.54±2.48	(-2.45, -0.64)
Limited	-1.29 ± 1.72	(2.65, 0.07)	-1.15±1.08	(-2.10, -0.21)	-0.77±1.37	(-1.68, 0.14)
Knee Var						
Normal	13.41 ± 10.47	(7.95, 18.87)	11.25±10.96	(7.19, 15.32)	11.80±8.87	(8.18, 15.43)
Limited	17.14 ± 13.48	(11.68, 22.61)	10.45±6.40	(6.39, 14.52)	12.99±7.03	(9.36, 16.62)
Knee ER						
Normal	-5.59 ± 7.82	(-8.38, -2.81)	-6.36±5.46	(-8.74, -3.97)	-3.78±5.03	(-5.74, -1.81)
Limited	-3.60 ± 3.80	(-6.38, -0.81)	-5.32±5.07	(-7.71, -2.94)	-1.79±3.51	(-3.75, 0.18)
Knee IR						
Normal	14.87 ± 14.92	(8.63, 21.11)	5.90±5.38	(3.84, 7.95)	15.70±15.83	(9.75, 21.65)
Limited	11.11 ± 12.56	(4.87, 17.36)	4.04±3.51	(1.98, 6.09)	12.12±9.76	(6.17, 18.07)
Ankle DF						
Normal	-30.03 ± 7.45	(-32.96, -27.11)	-29.02±5.84	(-31.68, -26.36)	-52.02±19.11	(-60.03, -44.02)
Limited	-26.14 ± 5.28	(-29.06, -23.21)	-25.89±5.90	(-28.54, -23.23)	-52.71±16.14	(-60.72, -44.71)

Table 9. Group Comparisons of Knee and Ankle Kinematics (Means ± SD) for the passive DF knee bent range of motion tertiles for each task (OHS, SLS, JL) with 95% Confidence Intervals (CI).

DSP	Overhead Squat		Single Leg Squat		Jump Landing	
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
Knee Flex						
Normal	*104.61 ± 13.37	(96.64, 112.58)	*76.30 ± 10.10	(70.03, 82.63)	77.29±16.92	(62.58, 81.94)
Limited	*87.79 ± 14.46	(79.82, 95.77)	*65.83 ±11.73	(59.57, 72.10)	72.26±16.90	(67.62, 86.98)
Knee Vlg						
Normal	-2.53 ± 4.30	(-4.45, -0.61)	-2.33 ±2.67	(-3.44, -1.22)	-0.75±1.23	(-1.55, 0.054)
Limited	-1.27 ± 1.99	(-3.19, 0.65)	-0.81±0.62	(-1.91, 0.30)	-0.80±1.55	(-1.60, 0.001)
Knee Var						
Normal	15.02± 11.23	(7.22, 22.82)	13.34±11.92	(7.96, 18.72)	12.83±8.33	(8.26, 17.40)
Limited	19.03 ± 15.66	(11.23, 26.84)	11.92±5.87	(6.54, 17.30)	12.98±7.64	(8.41, 17.56)
Knee ER						
Normal	-6.64 ± 9.17	(-10.57, -2.715)	-6.20±4.32	(-8.53, -3.87)	**-3.54±4.99	(-5.64, -1.44)
Limited	-3.44 ± 3.20	(-7.37, 0.49)	-4.87±3.80	(-7.20, -2.54)	** -0.65±1.42	(-2.75,1.46)
Knee IR						
Normal	15.80 ± 16.36	(6.88, 24.73)	6.28±6.20	(3.43, 9.13)	17.63±17.29	(9.45, 25.82)
Limited	11.23 ± 14.79	(2.31, 20.16)	3.78±3.80	(0.92, 6.63)	13.45±10.47	(5.27, 21.64)
Ankle DF						
Normal	*-33.25± 6.45	(-36.69, -29.80)	*-31.39±5.58	(-34.83, -27.95)	-52.94±20.47	(-63.88, -42.00)
Limited	*-25.69± 5.55	(-29.14, -22.25)	*-25.37±6.41	(-28.81, -21.94)	-49.89±17.65	(-60.83, -38.95)

*Significant group differences $p<0.05$

**Approaching significance $p=0.056$

Table 10. Group Comparisons of Knee and Ankle Kinematics (Means ± SD) for the WBLT tertiles for each task (OHS, SLS, JL) with 95% Confidence Intervals (CI).

DSP	**Overhead Squat**		**Single Leg Squat**		**Jump Landing**	
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
Knee Flex						
Normal	*107.13 ± 11.84	(100.17, 114.09)	*78.81 ± 9.55	(73.53, 84.09)	77.49±17.09	(69.04, 85.94)
Limited	*86.45 ± 12.47	(79.49, 93.41)	*62.35 ±8.90	(57.07, 67.64)	72.39±11.98	(63.95, 80.84)
Knee Vlg						
Normal	-2.23 ± 4.31	(-4.27, -0.20)	-2.00 ±2.60	(-3.41, -0.59)	-0.73±1.19	(-1.97, 0.52)
Limited	-2.16 ± 2.59	(-4.20, -0.13)	-2.10±2.32	(-3.51, -0.69)	-1.50±2.86	(-2.76, -0.25)
Knee Var						
Normal	16.05± 10.67	(7.72, 24.38)	*14.63±11.20	(10.60, 19.66)	12.73±8.17	(8.07, 17.38)
Limited	15.98 ± 17.60	(7.65, 24.31)	*6.99±5.38	(1.96, 12.02)	12.59±8.09	(7.94, 17.25)
Knee ER						
Normal	-6.01 ± 9.44	(-10.21, -1.80)	-5.28±4.02	(-8.61, -1.96)	-3.15±5.11	(-6.11, -0.18)
Limited	-5.11 ± 4.35	(-9.31, -0.90)	-7.34±7.17	(-10.67, -4.02)	-3.46±5.24	(-6.43, -0.50)
Knee IR						
Normal	17.49 ± 15.23	(8.82, 26.16)	6.81±5.90	(3.99, 9.63)	18.07±16.86	(10.40, 25.75)
Limited	9.63 ± 15.06	(0.96, 18.30)	4.04±3.69	(1.22, 6.86)	10.12±8.70	(2.34, 17.70)
Ankle DF						
Normal	*-33.86± 5.84	(-36.62, -31.10)	*-32.52±5.50	(-35.55, -29.49)	-52.36±19.90	(-61.73, -42.98)
Limited	*-23.39± 3.53	(-26.15, -20.63)	*-23.51±5.07	(-26.54, -20.49)	-56.67±11.84	(-66.04, -47.30)

*Significant group differences $p < .05$

Table 11. Effect Sizes for all Significant Results

	Knee Bent	**WBLT angle**
Knee Flx DSP (OHS)	1.21	1.70
Ankle DF DSP (OHS)	1.26	2.23
Knee Flx DSP (SLS)	0.96	1.78
Ankle Flx DSP (SLS)	1.00	1.70
Knee Varus DSP (SLS)	**	0.92
Knee ER DSP (JL)	1.08	**

Table 12. Intraclass Correlation Coefficients (ICC) and Standard Error of Measurements (SEM) for passive range of motion measurements and ankle arthrometer measurement

Measurement	**ICC**	**SEM**
DF knee straight	.988	0.88º
DF knee bent	.898	2.58º
WBLT (cm)	.972	0.41
WBLT angle	.953	1.61º
AA ant/post (mm)	.983	0.40

Table 13. Age (yrs), Height (cm), Body Mass (kg) presented as Means±SD for each group

	Normal (n=20)	Limited (n=20)
Age	20.70 ± 1.98	19.45 ± 1.40
Height	172.33 ± 9.73	171.12 ± 8.64
Body Mass	70.13 ± 13.80	70.42 ± 12.50

Table 14. Range of motion measurements for each group presented as Means±SD

Measurement	Normal	Limited
DF knee straight (degrees)	16.78±2.21	1.63±2.58
DF knee bent (degrees)	22.28±4.49	8.52±3.76
WBLT (cm)	12.50±3.74	8.82±2.63
WBLT (degrees)	48.45±7.61	41.30±5.37
AA ant/post (mm)	9.30±3.28	8.27±2.84

Table 15. Group Comparisons of Knee and Ankle Kinematics (Means ± SD) for the Normal and Limited DF range of motion groups for each task (OHS, SLS, JL) with 95% Confidence Intervals (CI).

	Overhead Squat		**Single Leg Squat**		**Jump Landing**	
	Mean ± SD	95% CI	Mean ± SD	95% CI	Mean ± SD	95% CI
Knee Flex Max						
Normal	109.73±15.59	(102.84,116.63)	85.14±13.25	(79.36,90.93)	105.46±14.90	(98.69, 112.24)
Limited	100.43±14.87	(93.53, 107.32)	80.66±12.29	(74.87, 86.44)	104.60±15.04	(97.82, 111.37)
Knee Flex DSP						
Normal	100.38 ± 13.73	(93.68, 107.08)	75.58 ± 11.00	(67.02, 78.13)	76.14±14.72	(69.59, 82.70)
Limited	92.56 ± 15.79	(85.87, 99.26)	67.74 ±13.42	(62.20, 73.30)	74.38±14.23	(67.83, 80.93)
Knee Vlg Max						
Normal	-5.28±5.24	(-7.27, -3.29)	-4.89±5.38	(-6.90, -2.88)	-1.03±9.85	(-4.61, 2.55)
Limited	-5.25±3.34	(-7.24, -3.26)	-3.98±3.36	(-5.99, -1.97)	-1.75±5.31	(-5.33, 1.83)
Knee Vlg DSP						
Normal	-2.36 ± 3.86	(-3.72, -1.00)	-2.44 ±2.74	(-3.38, -1.50)	-1.54±2.48	(-2.45, -0.64)
Limited	-1.29 ± 1.72	(2.65, 0.07)	-1.15±1.08	(-2.10, -0.21)	-0.77±1.37	(-1.68, 0.14)
MKD						
Normal	0.01±0.02	(0.004,0.018)	0.03±0.02	(0.03, 0.04)	0.03±0.07	(0.01, 0.06)
Limited	0.01± 0.01	(0.001, 0.016)	0.03±0.01	(0.02, 0.04)	0.04± 0.08	(0.02, 0.07)
Ankle DF DSP						
Normal	-30.03 ± 7.45	(-32.96, -27.11)	-29.02±5.84	(-31.68, -26.36)	-52.02±19.11	(-60.03, -44.02)
Limited	-26.14 ± 5.28	(-29.06, -23.21)	-25.89±5.90	(-28.54, -23.23)	-52.71±16.14	(-60.72, -44.71)

Table 16. Linear Correlation Results (r-value)

Ankle DF DSP	WBLT cm r-value	WBLT Angle r-value	DF knee Straight r-value	DF Knee Bent r-value	AA r-value
OHS	*-0.653	* -0.731	-0.298	*-0.396	*-0.323
SLS	*-0.538	*-0.636	-0.313	*-0.452	*-0.433
JL	*0.241	*0.199	0.007	-0.069	0.043

*Significant Correlation

Table 17. Observed Power and Effect Size for each kinematic variable

Variable	Effect Size	Observed Power
Knee Flx Max	.089	.469
Knee Flx DSP	.068	.370
Knee Vlg Max	.000	.050
Knee Vlg DSP	.032	.196
MKD Max	.007	.080
MKD	.025	.159
Ankle DF DSP	.087	.460

Appendix 2

Figures

Figure 1. DF knee straight measurement

Figure 2. DF knee bent measurement

Figure 3. Weight Bearing Lunge Technique

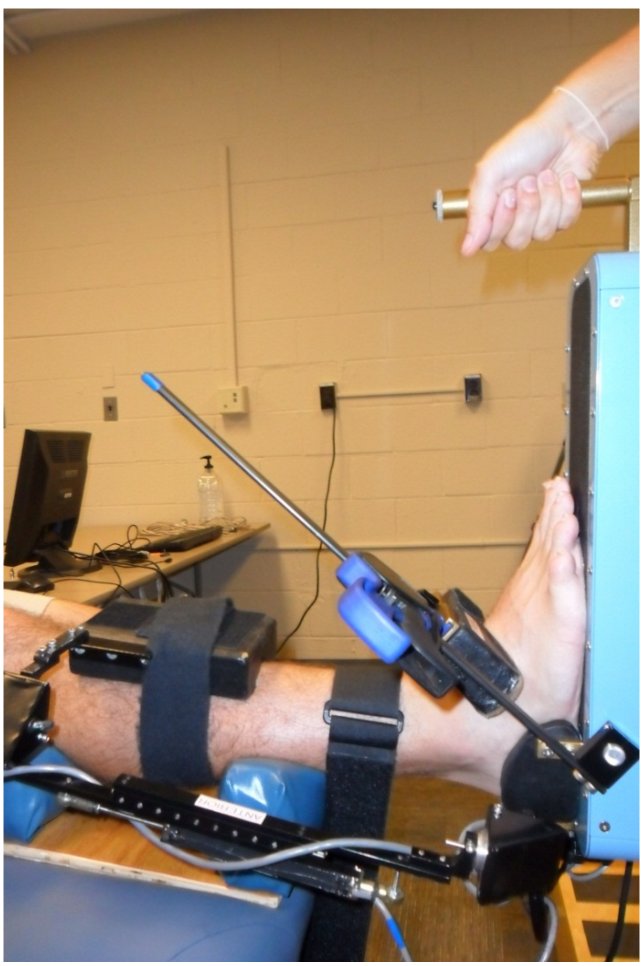

Figure 4. Ankle Arthrometer

Figure 5. Overhead Squat

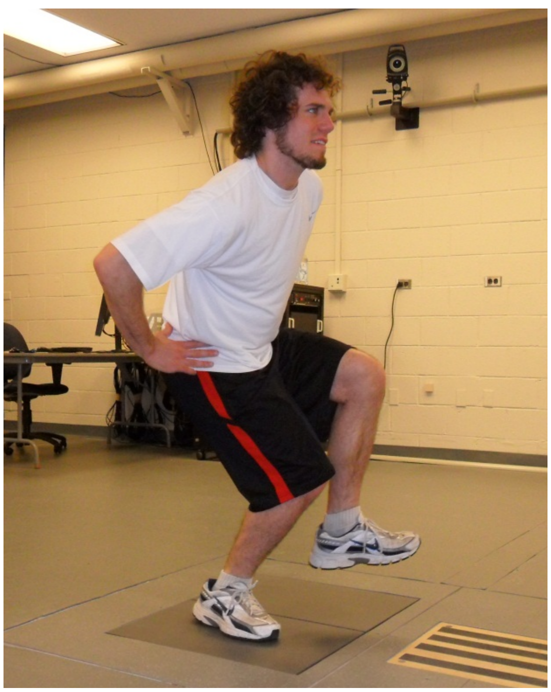

Figure 6. Single Leg Squat

Figure 7. Jump Landing Task

Appendix 3

Consent Form

University of North Carolina-Chapel Hill
Consent to Participate in a Research Study
Adult Subjects
Biomedical Form

IRB Study #:
Consent Form Version Date:

Title of Study: The Effects of Limited Ankle Dorsiflexion Range of Motion on Knee and Ankle Kinematics

Principal Investigator: Karli Dill, BS, LAT, ATC
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<u>What are some general things you should know about research studies?</u>

You are being asked to take part in a research study. To join the study is voluntary. You may refuse to join, or you may withdraw your consent to be in the study, for any reason.

Research studies are designed to obtain new knowledge that may help other people in the future. You may not receive any direct benefit from being in the research study. There also may be risks to being in research studies.

Deciding not to be in the study or leaving the study before it is done will not affect your relationship with the researcher, your health care provider, or the University of North Carolina-Chapel Hill. If you are a patient with an illness, you do not have to be in the research study in order to receive health care.

Details about this study are discussed below. It is important that you understand this information so that you can make an informed choice about being in this research study. You will be given a copy of this consent form. You should ask the researchers named above, or staff members who may assist them, any questions you have about this study at any time.

What is the purpose of this study?

The purpose of this study is to compare individuals with limited ankle motion to individuals with normal ankle motion on knee and ankle motion during three athletic tasks. In addition, some participants will perform stretching exercises to assess how stretching influences ankle and knee motion. The comparison of this data will help the sports medicine community understand the effects of limited ankle motion on knee and ankle motion and could help improve injury prevention programs.

Are there any reasons you should not be in this study?

You should not participate in this study if any of the following apply to you:

- You are not between the ages of 18-25
- You have any current symptoms of musculoskeletal injury (redness, swelling, pain)
- You have a history of musculoskeletal injuries that have occurred within the past 6 months that limited your physical activity for more than two days.
- You have a history of lower extremity surgery
- You have vestibular or balance disorders
- You have a known neurological disorder
- You are pregnant

How many people will take part in this study?

If you decide to be in this study, you will be one of 40 participants in this study.

How long will your part in this study last?

Your participation in this study will be an initial screening session that will last approximately 5 minutes. If you are eligible to participate in the study based on ankle range of motion you will return to the Sports Medicine Research Lab for a single testing session lasting approximately one hour.

What will happen if you take part in the study?

Before you participate in this study, you will read and sign an informed consent form. If you have any questions about the study in general, you can ask the researchers at any point during data collection. After you sign the consent form, you will be asked to answer questions regarding your injury history and physical activity level.

After completing the forms and questionnaires you will perform a five minute warm-up on a stationary bike. Once you have completed the warm-up the following procedures will begin:

a) Lower Extremity Range of Motion (Flexibility)

How far you can bend your ankle toward your nose will be measured using a standard goniometer. You will lie face down on a table and bend your ankle toward your nose. The principal investigator will apply overpressure to your foot and measure the angle formed at your ankle. The same procedure will be performed with your knee bent to 90º. A weight bearing lunge will be performed to measure ankle flexibility while standing, and A/P talar glide will be measured using an ankle arthrometer.

b) Overhead Squat

You will be asked to perform a double leg squat with your arms extended up overhead. In this task, you will stand with feet placed shoulder-distance apart while standing on force measuring devices. Your squat depth will be set at 60º by measuring the angle at your knee. You will lower your body into a squat to 60º, and then return to the initial starting position (upright). You will perform 5 trials of this task.

c) Single-Leg Squat

You will be asked to perform a single-leg squat while keeping your hands on your hips. In this task, you will be asked to stand with feet placed shoulder-distance apart while standing on force measuring devices. You will then raise one foot about 5-10cm so that you are balancing on one leg. You will then lower your body into a single-leg squat to 60º and then return to the initial starting position (upright). You will perform 5 trials of this task on each leg.

d) Jump Landing

The jump landing task involves a dropping from a 30cm box to the ground and then immediately jumping in the air for maximal height. You will jump down and forwards towards a target that is placed a set distance in front of the box (50% of your height). You will be instructed to jump onto the force measuring device and immediately recoil and perform a second vertical jump for maximal height. You will perform 5 trials of this task.

e) Stretching Intervention

You will be randomly assigned to either perform a stretching program or to rest for a period of seven minutes. If you are in the stretching group, immediately after the completion of the three above tasks you will be asked to perform three phases of stretching; myofascial release (foam rolling) for two minutes, static stretching for two minutes, myofascial release (foam rolling) for one additional minute. If you are in the non-stretching group, immediately upon the completion of the three above tasks you will be asked to sit in a relaxed position for the same duration of time that the stretching protocol would take.

At the completion of the stretching or non-stretching intervention, two of the range of motion assessments from earlier will be performed again. In addition, you will be asked to repeat the single-leg squat and jump landing tasks.

<u>What are the possible benefits from being in this study?</u>

It is unlikely that you will see any noticeable benefits from participation in this study. If you are an individual with limited ankle motion, you may learn the effects of limited ankle motion on knee and ankle kinematics and how it relates to injury risk. Furthermore, the sports medicine community may learn the importance of proper ankle motion in relationship to injury risk.

What are the possible risks or discomforts involved with being in this study?

This study involves squatting and jumping tasks that may present the following risks to you:

- Possibility of a ligament injury to the joints of your lower extremities
- Possibility of muscle strains/pulls/soreness in your lower extremities
- There may be uncommon or previously unrecognized risks that might occur

No penalty will be incurred if you decide not to participate in this study. Please do not feel pressured to participate, or continue with the study if at any point you feel uncomfortable.

What if we learn about new findings or information during the study?

You will be given any new information gained during the course of the study that might affect your willingness to continue your participation.

How will your privacy be protected?

No subjects will be identified in any report or publication about this study. Although every effort will be made to keep research records private, there may be times when federal or state law requires the disclosure of such records, including personal information. This is very unlikely, but if disclosure is ever required, UNC-Chapel Hill will take steps allowable by law to protect the privacy of personal information. In some cases, your information in this research study could be reviewed by representatives of the University, research sponsors, or government agencies for purposes such as quality control or safety.

What will happen if you are injured by this research?

All research involves a chance that something bad might happen to you. This may include the risk of personal injury. In spite of all safety measures, you might develop a reaction or injury from being in this study. If such problems occur, the researchers will help you get medical care, but any costs for the medical care will be billed to you and/or your insurance company. The University of North Carolina at Chapel Hill has not set aside funds to pay you for any such reactions or injuries, or for the related medical care. However, by signing this form, you do not give up any of your legal rights.

What if you want to stop before your part in the study is complete?

You can withdraw from this study at any time, without penalty. The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

Will you receive anything for being in this study?

You will not receive any compensation for taking part in this study.

Will it cost you anything to be in this study?

It will not cost you anything to participate in this study. The study will not cover any medical fee (surgery/physical therapy etc.)

What if you are a UNC student?

You may choose not to be in the study or to stop being in the study before it is over at any time. This will not affect your class standing or grades at UNC-Chapel Hill. You will not be offered or receive any special consideration if you take part in this research.

What if you are a UNC employee?

Taking part in this research is not a part of your University duties, and refusing will not affect your job. You will not be offered or receive any special job-related consideration if you take part in this research.

What if you have questions about this study?

You have the right to ask any questions you may have about this research study. If you have any questions about this study, or if a research-related injury occurs, you should contact the researchers listed on the first page of this form.

What if you have questions about your rights as a research subject?

All research on human volunteers is reviewed by a committee that works to protect your rights and welfare. If you have questions or concerns about your rights as a research subject you may contact, anonymously if you wish, the Institutional Review Board at 919-966-3113 or by email to IRB_subjects@unc.edu.

- -

Subject's Agreement:

I have read the information provided above. I have asked all the questions I have at this time. I voluntarily agree to participate in this research study.

____ __________________

Signature of Research Subject Date

____

Printed Name of Research Subject

Signature of Person Obtaining Consent Date

Printed Name of Person Obtaining Consent

Appendix 4

Health History Questionnaire

SUBJECT ID: ______________________ Today's Date: _______/_______/_______

HEALTH AND ACTIVITY QUESTIONNAIRE

The Effects of Limited Ankle Dorsiflexion Range of Motion on Knee and Ankle Kinematics

Part 1: DEMOGRAPHICS

1. What is your age? _________________

2. What is your gender? Male Female

3. If you were going to kick a ball for maximum distance, which leg would you use? RIGHT LEFT

____

Part 3: PHYSICAL ACTIVITY HISTORY

13. On average, how many days per week do you currently participate in physical activity? ________________

____

14. On average, how many minutes do you exercise per day? ________________
Please describe the types of physical activity you perform.
(running, weight-lifting, stairmaster, elliptical, etc.)

____

15. Have you ever or do you currently participate in organized athletics? YES NO

15a. If you answered YES to the above, please indicate what organized sport(s).

____

____

____

____

15b. Did or do you play at the following levels?

High school varsity (if yes, # years):	YES	NO
Travel team/club/AAU/other (if yes, # years):	YES	NO
College varsity intercollegiate (if yes, # years):	YES	NO
College intramural (if yes, # years):	YES	NO
Other competitive level (describe):	YES	NO

---

16. Have you ever participated in high endurance exercise (cross-country, distance running, marathons, triathlons, etc) YES NO

16a. If YES, please explain:

---

17. Have you, in the past 12 months, participated in any type of plyometric training program (jump training, box training)? YES NO

17a. If YES, please explain:

---

18. Have you, in the past 12 months, participated in any type of weight training program? YES NO

18a. If YES, please explain:

---

19. Have you ever participated in an ACL injury prevention program? YES NO

19a. If YES, please explain when and for how long:

19b. If YES, please explain the program:

---

20. Have you ever participated in a core-strengthening program? (abdominal crunches, sit-ups, planks, back extensions, "supermans", etc.) YES NO

20a. If you answered YES to the above please briefly describe the type of core strengthening exercises you have performed:

Part 4: GENERAL HEALTH HISTORY

21. Are you currently in good health? YES NO

22. Have you ever been diagnosed with any cardiac condition YES NO
(such as tachycardia, bradycardia, fibrillation, heart murmur, etc.)?

22a. If YES, please explain:

23. Have you ever been diagnosed with any neurologic condition (such as brain injury, spinal cord injury, Parkinson's disease, multiple sclerosis, epilepsy, etc.) YES NO

23a. If YES, please explain:

24. Have you ever had asthma? YES NO

24a. If YES, do you still take medications?

25. Do you have diabetes? YES NO

26. Have you ever been diagnosed with high blood pressure? YES NO
(Greater than 140/90)

27. Have you ever experienced heat stroke or heat exhaustion? YES NO

27a. If YES, when?

28. Have you ever needed hospitalization for a non-surgical YES NO

reason?

28a. If YES, why were you hospitalized?

28b. If YES, when were you hospitalized?

---

29. Have you ever had surgery? YES NO

29a. If YES, when did you have surgery?

29b. If YES, what surgical procedure was performed?

---

30. Have you ever felt dizzy, or fainted, during or after exercise? YES NO

30a. If YES, how often has it occurred?

30b. If YES, when was the last time this occurred?

---

31. Are you currently taking any medications (prescription or non-prescription)? YES NO

31a. If YES, please explain:

---

32. Have you experienced an infectious disease (such as mononucleosis, pneumonia, hepatitis, influenza, strep throat) in the past year (this excludes the common cold)? YES NO

---

33. Do you have any drug, latex, or food allergies? YES NO

33a. If YES, please explain:

---

34. In the past year, have you been under the care of a physician for ANY reason? YES NO

34a. If YES, please explain:

Part 5: FAMILY HEALTH HISTORY

35. Has a blood relative ever been diagnosed with any of the following?

(If YES, please indicate their relation to you)

35a. Any Cardiac Disease	YES	NO
35b. Heart Attach (Before age 55)	YES	NO
35c. Diabetes (Type I or Type II)	YES	NO
35d. Marfan's Syndrome	YES	NO
35e. Aneurysm	YES	NO
35f. High blood pressure	YES	NO
35g. Any bone/joint disease (osteoporosis, arthritis,etc.)	YES	NO

---

36. Has any blood relative died prior to the age of 50? YES NO

36a. If YES, please explain reason and age:

Part 6: BONE AND JOINT INJURY HISTORY

37. Have you ever had a fracture in any part of your body? YES NO

(if more than one area, list all below)

37a. If YES, where?

37b. If YES, when?

37c. If YES, did it require surgery? YES NO

---

38. Have you ever had an injury to one of the following UPPER BODY joints or body regions (if YES, please explain next to the joint/body region, indicate the date the injury occurred, and indicate the side, circle both Right and Left if you had injury to both sides)?

38a. Neck RIGHT LEFT

38b. Upper back (thoracic spine)	RIGHT LEFT
38c. Lower back (lumbar spine)	RIGHT LEFT
38d. Pelvis	RIGHT LEFT
38e. Shoulder	RIGHT LEFT
38f. Elbow	RIGHT LEFT
38g. Wrist	RIGHT LEFT
38h. Hand/Fingers	RIGHT LEFT
38i. Abdominal wall	YES NO

---

39. Have you ever had any of the following LOWER BODY injuries (if YES, please explain next to injury, indicate the date the injury occurred, and indicate the side, circle both Right and Left if you had injury to both sides)?

39a. Hip joint sprain	RIGHT LEFT
39b. Hip joint cartilage damage	RIGHT LEFT
39c. Hip bursitis	RIGHT LEFT
39d. Hip flexor strain	RIGHT LEFT
39e. Quadriceps muscle strain	RIGHT LEFT
39f. Hamstring muscle strain	RIGHT LEFT
39g. Groin (hip adductor) strain	RIGHT LEFT
39h. Iliotibial band syndrome (IT band)	RIGHT LEFT
39i. Patellofemoral pain syndrome (anterior knee pain, pain in front of knee, “kneecap” pain)?	RIGHT LEFT
39j. Patella (kneecap) dislocation	RIGHT LEFT
39k. Knee bursitis	RIGHT LEFT
39l. Patellar tendinitis (runner’s knee, jumper’s knee)	RIGHT LEFT
39m. Anterior cruciate ligament (ACL) injury	RIGHT LEFT
39n. Posterior cruciate ligament (PCL) injury	RIGHT LEFT
39o. Medial collateral ligament (MCL) injury	RIGHT LEFT

39p. Lateral collateral ligament injury	RIGHT LEFT
39q. Meniscus/cartilage injury in the knee	RIGHT LEFT
39r. “Shin splints” (medial tibial stress syndrome)	RIGHT LEFT
39s. Compartment syndrome	RIGHT LEFT
39t. Lateral (inversion) ankle sprain	RIGHT LEFT
39u. Medial (eversion) ankle sprain	RIGHT LEFT
39v. Bursitis (heel, ankle, or foot)	RIGHT LEFT
39w. Tendinitis (Achilles, ankle, foot)	RIGHT LEFT
39x. Bunions	RIGHT LEFT

40. Please place a STAR (*) next to any of the above injuries (items 18-19) that prevented you from participating in physical activity for two or more days

41. Please CIRCLE any of the above injuries (items 18-19) where you saw a doctor.

---

42. Have you ever worn orthotics in your shoes?	YES	NO
42a. If YES, are you currently using orthotics?	YES	NO
42b. If YES, are they store-bought?	YES	NO

---

43. Are you currently experiencing any symptoms (pain, swelling, etc.) of any lower body, lower back, or abdominal wall injury?	YES	NO

Appendix 5

Lysholm Knee Scoring Scale

LYSHOLM KNEE SCORING SCALE

Instructions: Below are common complaints which people frequently have with their knee problems. Please check the statement which best describes your condition.

I. LIMP:

I have no limp when I walk. (5)
_____ I have a slight or periodical limp when I walk. (3)
_____ I have a severe and constant limp when I walk. (0)

II. USING CANE OR CRUTCHES

_____ I do not use a cane or crutches. (5)
I use a cane or crutches with some weight-bearing. (2)
_____ Putting weight on my hurt leg is impossible. (0)

III. LOCKING SENSATION IN THE KNEE

_____ I have no locking and no catching sensations in my knee. (15)
_____ I have catching sensation but no locking sensation in my knee. (10)
_____ My knee locks occasionally. (6)
_____ My knee locks frequently. (2)
My knee feels locked at this moment. (0)

IV. GIVING WAY SENSATION FROM THE KNEE

____ My knee never gives way. (25)
____ My knee rarely gives way, only during athletics or other vigorous activities. (20)
____ My knee frequently gives way during athletics or other vigorous activities, in turn I am unable to participate in these activities. (15)
____ My knee occasionally gives way during daily activities. (10)
____ My knee often gives way during daily activities. (5)
____ My knee gives way every step I take. (0)

V. PAIN:

I have no pain in my knee. (25)
____ I have intermittent or slight pain in my knee during vigorous activities. (20)
____ I have marked pain in my knee during vigorous activities. (15)
____ I have marked pain in my knee during or after walking more than 1 mile. (10)
I have marked pain in my knee during or after walking less than 1 mile. (5)
____ I have constant pain in my knee. (0)

VI. SWELLING

____ I have no swelling in my knee. (10)
____ I have swelling in my knee only after vigorous activities. (6)
____ I have swelling in my knee after ordinary activities. (2)
____ I have swelling constantly in my knee. (0)

VII. CLIMBING STAIRS:

____ I have no problems climbing stairs. (10)
____ I have slight problems climbing stairs. (6)
____ I can climb stairs only one at a time. (2)
Climbing stairs is impossible for me. (0)

VIII. SQUATTING

I have no problems squatting. (5)
____ I have slight problems squatting. (4)
____ I can not squat beyond a 90 degree bend in my knee. (2)
____ Squatting is impossible because of my knee. (0)

TOTAL_____/100

INSTRUCTIONS: Please place an X on the line to indicate the amount of pain you have had in your knee(s) the past 24 hours. The scale ranges from "no pain at all" to the "worst possible pain".

RIGHT KNEE ____
no pain ... worst possible pain

LEFT KNEE ____
no pain ... worst possible pain

Appendix 6

Foot and Ankle Ability Measure

Foot and Ankle Ability Measure (FAAM)
Activities of Daily Living Subscale

Please Answer **every question** with **one response** that most closely describes your condition within the past week.
If the activity in question is limited by something other than your foot or ankle mark "Not Applicable" (N/A).

	No Difficulty	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Standing	☐	☐	☐	☐	☐	☐
Walking on even Ground	☐	☐	☐	☐	☐	☐
Walking on even ground without shoes	☐	☐	☐	☐	☐	☐
Walking up hills	☐	☐	☐	☐	☐	☐
Walking down hills	☐	☐	☐	☐	☐	☐
Going up stairs	☐	☐	☐	☐	☐	☐
Going down stairs	☐	☐	☐	☐	☐	☐
Walking on uneven ground	☐	☐	☐	☐	☐	☐
Stepping up and down curbs	☐	☐	☐	☐	☐	☐
Squatting	☐	☐	☐	☐	☐	☐
Coming up on your toes	☐	☐	☐	☐	☐	☐
Walking initially	☐	☐	☐	☐	☐	☐
Walking 5 minutes or less	☐	☐	☐	☐	☐	☐
Walking approximately 10 minutes	☐	☐	☐	☐	☐	☐
Walking 15 minutes or greater	☐	☐	☐	☐	☐	☐

Because of your foot and ankle how much difficulty do you have with:

	No Difficulty at all	Slight Difficulty	Moderate Difficulty	Extreme Difficulty	Unable to do	N/A
Home responsibilities	☐	☐	☐	☐	☐	☐
Activities of daily living	☐	☐	☐	☐	☐	☐
Personal care	☐	☐	☐	☐	☐	☐
Light to moderate work (standing, walking)	☐	☐	☐	☐	☐	☐
Heavy work (push/pulling, climbing, carrying)	☐	☐	☐	☐	☐	☐
Recreational activities	☐	☐	☐	☐	☐	☐

How would you rate your current level of function during you usual activities of daily living from 0 to 100 with 100 being your level of function prior to your foot or ankle problem and 0 being the inability to perform any of your usual daily activities.

__ __ __ . 0 %

Martin, R; Irrgang, J; Burdett, R; Conti, S; VanSwearingen, J: Evidence of Validity for the Foot and Ankle Ability Measure. Foot and Ankle International. Vol.26, No.11: 968-983, 2005.

Appendix 7

Supplementary Results and Discussion

Results

Intra class correlation coefficients were calculated to determine intra-rater reliability for the range of motion assessments. The results were strong for both the passive dorsiflexion measurement with the knee straight (ICC (3,k)=0.988, SEM=0.88º), knee bent (ICC (3,k)=0.898, SEM=2.58º), the WBLT centimeter measure (ICC (3,k)=0.972, SEM=0.41cm), the WBLT angle measurement (ICC(3,k)=0.953, SEM=1.61º), and the ankle arthrometer (ICC(3,k)=0.983, SEM=0.40mm) (Table 12).

Forty subjects participated in this study with 20 subjects in each group, limited and normal. Means and standard deviations for all age, height, and body mass measures are presented in Table 13. Three separate independent samples t-tests were performed to compare the NORM and LIM groups. No significant differences were observed between groups on height ($t_{38} = .418$, $P = .678$) and body mass ($t_{38} = -.070$, $P = .945$). Significant group differences were observed in age ($t_{38} = 2.311$, $P = .026$), however the mean difference between groups was 1.25 years so we feel comfortable comparing these groups. The means and standard deviations for all of the range of motion measurements according to group, including the ankle arthrometer are presented in Table 14.

Three separate one-way ANOVA’s were performed to compare groups on knee and ankle kinematic data for each task. No significant differences were observed between the NORM and LIM groups on peak knee flexion, knee flexion displacement, peak knee valgus, knee valgus displacement, medial knee displacement, or ankle dorsiflexion displacement for any of the tasks (Table 15).

Correlational analyses were performed to observe the relationship between all of the ankle range of motion measurements and ankle dorsiflexion displacement during each of the three tasks. The WBLT angle was strongly correlated with dorsiflexion displacement during the OHS (r= -0.731, p<0.000) and moderately correlated with dorsiflexion displacement during the SLS (r= -0.636, p<0.001). A moderate correlation also existed between the WBLT centimeter measurement and dorsiflexion displacement during the OHS (r= -0.653, p<0.001) and SLS (r= -0.538, p<0.001). The arthrokinematic measurements taken with the ankle arthrometer and the passive dorsiflexion measurements with the knee straight and bent, showed low correlations with ankle dorsiflexion displacement during any of the tasks (Table 16).

The observed power (range = .000-.089) and effect size (range = .05-.47) for each of the kinematic variables is presented in Table 17.

Discussion

The most significant finding in this study is that when identifying limited and normal range of motion via a passive, knee straight measurement, there were no differences between groups. Previous research has suggested that individuals with limited passive dorsiflexion range of motion have used faulty lower extremity kinematics during functional tasks (Bell, Padua et al. 2008; Sigward, Ota et al. 2008). However, their significant findings were related to dorsiflexion with the knee bent, not with the knee straight. This might suggest that a knee bent measurement may be better at discriminating knee kinematics during functional movement simply due to the similarities in the task. Functional movement frequently occurs when the knee is bent and perhaps, the knee straight measurement is unable to represent functional range of motion.

Fong et al. (Fong, Blackburn et al. 2011) identified differences in individuals with limited dorsiflexion range of motion in regards to knee flexion angles during a landing task. They found that individuals with limited dorsiflexion range of motion measured with the knee straight had lesser knee flexion angles, which is dissimilar to our results. A possible explanation for the contradiction in results is the differences in the jump landing tasks that were used. We had subjects perform a landing from a 30-cm box at a distance of 50% of their standing height from the force place with an immediate countermovement into a maximal vertical jump. Fong et al. (Fong, Blackburn et al. 2011) had subjects jump forward from a similar height box at a distance of 40% of their standing height. They did not incorporate a maximal vertical jump after landing as they were attempting to isolate the biomechanical control of the loading phase in association with ankle movement. Our subjects were preparing for a quick vertical jump so perhaps they did not utilize greater knee flexion even if they were capable simply because of our task.

The most important finding from the correlation analysis was that the WBLT angle measurement showed stronger correlations with ankle dorsiflexion displacement during the squatting tasks than any of the other measurements. This result may be expected because of the weight bearing nature of the measurement and the similar movement that is incorporated in both the WBLT and squatting tasks. The WBLT cm measurement also showed moderate correlations with ankle dorsiflexion during the SLS and OHS but this correlation was not strong as the WBLT angle. This may be the case because the WBLT cm measurement cannot adjust for the length of the shank or the foot. The angle measurement does not need to adjust for these factors because it is measuring strictly the angle of the tibia relative to the vertical.

The WBLT angle may be a better functional representation of dorsiflexion range of motion. The increased torque that is placed on the ankle during the WBLT may require the individual to reach maximum dorsiflexion, unlike passive assessments. The passive measurements showed low correlations with ankle dorsiflexion displacement during any of the tasks, which might suggest that passive measurements may not represent the amount of motion an individual utilizes during functional tasks. This may explain why there were no significant differences between groups in this study. These findings suggest that the WBLT may be an additional tool, along with passive range of motion, to use in a clinical setting for a variety of measurements to help identify an individual's dorsiflexion range of motion and how that individual will use that range of motion during functional tasks.

This study is not without limitations. The investigators were not blinded to the subjects' group assignment which may have caused unintentional bias during range of motion measurements. We also used specific criteria to assign groups so the results may only be applicable to individuals who meet those criteria and may not be applicable to the general population. We did not assess muscle activation or strength during this study and both are shown to affect kinematics at the knee.

There is a need for continued research in this area. It needs to be determined whether a WBLT is more efficient than passive ankle dorsiflexion measurements in identifying individuals with faulty knee kinematics. This would help improve the current knowledge on the role of dorsiflexion range of motion in knee and ankle kinematics as well as establish a clinical tool for identifying individuals susceptible to faulty knee kinematics.

References

Agel, J., E. A. Arendt, et al. (2005). "Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review." American Journal of Sports Medicine **33**(4): 524-530.

Arendt, E. A., J. Agel, et al. (1999). "Anterior cruciate ligament injury patterns among collegiate men and women." Journal of Athletic Training **34**(2): 86-92.

Bell, A. L., D. R. Pedersen, et al. (1990). "A comparison of the accuracy of several hip center location prediction methods." J Biomech **23**(6): 617-621.

Bell, D. R., D. A. Padua, et al. (2008). "Muscle strength and flexibility characteristics of people displaying excessive medial knee displacement." Archives of Physical Medicine & Rehabilitation **89**(7): 1323-1328.

Bennell, K., R. Talbot, et al. (1998). "Intra-rater and inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion. ." Australian Journal of Physiotherapy(44): 175-180.

Beynnon, B. D., B. C. Fleming, et al. (1995). "Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo... presented at the joint meeting of the International Society of the Knee/International Arthroscopy Association of America, Copenhagen, Denmark, June 27, 1993." American Journal of Sports Medicine **23**(1): 24-34.

Beynnon, B. D., R. J. Johnson, et al. (1997). "The strain behavior of the anterior cruciate ligament during squatting and active flexion-extension: a comparison of an open and a closed kinetic chain exercise." American Journal of Sports Medicine **25**(6): 823-829.

Blackburn, J. T., M. F. Norcross, et al. (2011). "Influences of hamstring stiffness and strength on anterior knee joint stability." Clinical Biomechanics **26**(3): 278-283.

Blackburn, J. T. and D. A. Padua (2008). "Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing." Clinical Biomechanics **23**(3): 313-319.

Blackburn, J. T. and D. A. Padua (2009). "Sagittal-Plane Trunk Position, Landing Forces, and Quadriceps Electromyographic Activity." Journal of Athletic Training **44**(2): 174-179.

Boden, B. P., G. S. Dean, et al. (2000). "Mechanisms of anterior cruciate ligament injury." Orthopedics **23**(6): 573-578.

Claiborne, T. L., C. W. Armstrong, et al. (2006). "Relationship between hip and knee strength and knee valgus during a single leg squat." Journal of Applied Biomechanics **22**(1): 41-50.

Condon, S. M. and R. S. Hutton (1987). "Soleus Muscle Electromyographic Activity and Ankle Dorsiflexion Range of Motion During Four Stretching Procedures." Physical Therapy **67**(1): 24-30.

DeMorat, G., P. Weinhold, et al. (2004). "Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury." American Journal of Sports Medicine **32**(2): 477-483.

DiGiovanni, C. W., R. Kuo, et al. (2002). "ISOLATED GASTROCNEMIUS TIGHTNESS." Journal of Bone & Joint Surgery, American Volume **84**(6): 962-970.

DiStefano, L. J., D. A. Padua, et al. (2008). "Lower extremity kinematics and ground reaction forces after prophylactic lace-up ankle bracing." Journal of Athletic Training **43**(3): 234-241.

Durselen, L., L. Claes, et al. (1995). "The influence of muscle forces and external loads on cruciate ligament strain." American Journal of Sports Medicine **23**(1): 129-136.

Faunø, P. and B. Wulff Jakobsen (2006). "Mechanism of Anterior Cruciate Ligament Injuries in Soccer." Int J Sports Med **27**(01): 75,79.

Fong, C. M., J. T. Blackburn, et al. (2011). "Ankle-dorsiflexion range of motion and landing biomechanics." Journal of Athletic Training **46**(1): 5-10.

Ford, K. R., G. D. Myer, et al. (2003). "Valgus Knee Motion during Landing in High School Female and Male Basketball Players." Medicine & Science in Sports & Exercise **35**(10): 1745-1750.

Giffin, J. R., T. M. Vogrin, et al. (2004). "Effects of Increasing Tibial Slope on the Biomechanics of the Knee." The American Journal of Sports Medicine **32**(2): 376-382.

Green, T., K. Refshauge, et al. (2001). "A randomized controlled trial of a passive accessory joint mobilization on acute ankle inversion sprains." Physical Therapy **81**(4): 984-994.

Griffin, L., J. Agel, et al. (2000). "Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies." Journal of American Academy of Orthopaedic Surgeons **8**(3): 141-150.

Griffin, L. Y., M. J. Albohm, et al. (2006). "Understanding and Preventing Noncontact Anterior Cruciate Ligament Injuries." The American Journal of Sports Medicine **34**(9): 1512-1532.

Hewett, T. E., T. N. Lindenfeld, et al. (1999). "The Effect of Neuromuscular Training on the Incidence of Knee Injury in Female Athletes." The American Journal of Sports Medicine **27**(6): 699-706.

Hewett, T. E., G. D. Myer, et al. (2006). "Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors." Am J Sports Med **34**(2): 299-311.

Hollman, J. H., B. E. Ginos, et al. (2009). "Relationship between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down." Journal of Sport Rehabilitation **18**(1): 104-117.

Hubbard, T. J., T. W. Kaminski, et al. (2004). "Quantitative assessment of mechanical laxity in the functionally unstable ankle." Med Sci Sports Exerc **36**(5): 760-766.

Ireland, M. L. (1999). "Anterior cruciate ligament injury in female athletes: epidemiology." Journal of Athletic Training **34**(2): 150-154.

Kernozek, T. W., M. R. Torry, et al. (2005). "Gender Differences in Frontal and Sagittal Plane Biomechanics during Drop Landings." Medicine and Science in Sports and Exercise **37**(6): 1003-1012.

Kovaleski, J. E., L. R. Gurchiek, et al. (1999). "Instrumented measurement of anteroposterior and inversion-eversion laxity of the normal ankle joint complex." Foot Ankle Int **20**(12): 808-814.

Kovaleski, J. E., J. Hollis, et al. (2002). "Assessment of Ankle-Subtalar-Joint-Complex Laxity Using an Instrumented Ankle Arthrometer: An Experimental Cadaveric Investigation." J Athl Train **37**(4): 467-474.

LaPrade, R. F. and Q. M. Burnett (1994). "Femoral Intercondylar Notch Stenosis and Correlation to Anterior Cruciate Ligament Injuries." The American Journal of Sports Medicine **22**(2): 198-203.

Li, G., L. E. DeFrate, et al. (2005). "In vivo kinematics of the ACL during weight-bearing knee flexion." Journal of Orthopaedic Research **23**(2): 340-344.

Lohmander, L. S., A. Östenberg, et al. (2004). "High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury." Arthritis & Rheumatism **50**(10): 3145-3152.

Macrum, E., D. R. Bell, et al. (2011). "Limiting ankle dorsiflexion range of motion alters lower extremity kinematics and muscle activation patterns during a squat. ." Journal of Sport Rehabilitation.

Mahieu, N. N., E. Witvrouw, et al. (2006). "Improving strength and postural control in young skiers: whole-body vibration versus equivalent resistance training." Journal of Athletic Training **41**(3): 286-293.

Markolf, K. L., D. M. Burchfield, et al. (1995). "Combined knee loading states that generate high anterior cruciate ligament forces." J Orthop Res **13**(6): 930-935.

Martin, R., J. Irrgang, et al. (2005). "Evidence of validity for the foot and ankle ability measure (FAAM)." Foot & Ankle International **26**(11): 968-983.

Marx, R. G., E. C. Jones, et al. (2001). "Reliability, Validity, and Responsiveness of Four Knee Outcome Scales for Athletic Patients." Journal of Bone & Joint Surgery, American Volume **83**(10): 1459.

More, R. C., B. T. Karras, et al. (1993). "Hamstrings—an anterior cruciate ligament protagonist." The American Journal of Sports Medicine **21**(2): 231-237.

Moseley, A., J. Crosbie, et al. (2001). "Normative data for passive ankle plantarflexion-dorsiflexion flexibility." Clinical Biomechanics(16): 514-521.

Myer, G. D., K. R. Ford, et al. (2009). "The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes." Clinical Journal of Sport Medicine **19**(1): 3-8.

Neuman, D. A. (2010). Kinesiology of the musculoskeletal system: foundations for rehabilitation. St. Louis, Missouri, Mosby Elsevier.

Oh, Y. K., D. B. Lipps, et al. (2012). "What Strains the Anterior Cruciate Ligament During a Pivot Landing?" The American Journal of Sports Medicine **40**(3): 574-583.

Olsen, O.-E., G. Myklebust, et al. (2004). "Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball." The American Journal of Sports Medicine **32**(4): 1002-1012.

Orchard, J., H. Seward, et al. (2001). "Intrinsic and Extrinsic Risk Factors for Anterior Cruciate Ligament Injury in Australian Footballers." The American Journal of Sports Medicine **29**(2): 196-200.

Padua, D. A., S. W. Marshall, et al. (2009). "The Landing Error Scoring System (LESS) Is a Valid and Reliable Clinical Assessment Tool of Jump-Landing Biomechanics." The American Journal of Sports Medicine **37**(10): 1996-2002.

Peres, S., D. Draper, et al. (2002). "Pulsed shortwave diathermy and prolonged long-duration stretching increase dorsiflexion range of motion more than identical stretching without diathermy." Journal of Athletic Training **37**(1).

Piva, S., K. Fitzgerald, et al. (2006). "Reliability of measures of impairments associated with patellofemoral pain syndrome." BMC Musculoskeletal Disorders **7**(1): 33.

Piva, S. R., E. A. Goodnite, et al. (2005). "Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome." Journal of Orthopaedic & Sports Physical Therapy **35**(12): 793-801.

Pollard, C. D., S. M. Sigward, et al. (2007). "Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver." Clinical Journal of Sport Medicine **17**(1): 38-42.

Pollard, C. D., S. M. Sigward, et al. (2010). "Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments." Clinical Biomechanics **25**(2): 142-146.

Renström, P., S. W. Arms, et al. (1986). "Strain within the anterior cruciate ligament during hamstring and quadriceps activity*." The American Journal of Sports Medicine **14**(1): 83-87.

Roos, E. M. (2005). "Joint injury causes knee osteoarthritis in young adults." Current Opinion in Rheumatology **17**(2): 195-200.

Salmon, L., V. Russell, et al. (2005). "Incidence and Risk Factors for Graft Rupture and Contralateral Rupture After Anterior Cruciate Ligament Reconstruction." Arthroscopy: The Journal of Arthroscopic & Related Surgery **21**(8): 948-957.

Seeley, R., T. Stephens, et al. (2004). Anatomy and Physiology. Columbus, OH, McGraw Hill.

Sigward, S. M., S. Ota, et al. (2008). "Predictors of frontal plane knee excursion during a drop land in young female soccer players." Journal of Orthopaedic & Sports Physical Therapy **38**(11): 661-667.

Souryal, T. O. and T. R. Freeman (1993). "Intercondylar notch size and anterior cruciate ligament injuries in athletes." The American Journal of Sports Medicine **21**(4): 535-539.

Thoms, V. and K. Rome (1997). "Effect of subject position on the reliability of measurement of active ankle joint dorsiflexion." The Foot **7**(3): 153-158.

Vicenzino, B., M. Branjerdporn, et al. (2006). "Initial changes in posterior talar glide and dorsiflexion of the ankle after mobilization with movement in individuals with recurrent ankle sprain." Journal of Orthopaedic & Sports Physical Therapy **36**(7): 464-471.

von Porat, A., E. M. Roos, et al. (2004). "High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes." Annals of the Rheumatic Diseases **63**(3): 269-273.

Wiesler, E. R., D. M. Hunter, et al. (1996). "Ankle Flexibility and Injury Patterns in Dancers." The American Journal of Sports Medicine **24**(6): 754-757.

Willson, J. D., M. L. Ireland, et al. (2006). "Core strength and lower extremity alignment during single leg squats." Medicine & Science in Sports & Exercise **38**(5): 945-952.

Withrow, T. J., L. J. Huston, et al. (2006). "The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing." Clinical Biomechanics **21**(9): 977-983.

Withrow, T. J., L. J. Huston, et al. (2006). "The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing." American Journal of Sports Medicine **34**(2): 269-274.

Wright, R. W., W. R. Dunn, et al. (2007). "Risk of Tearing the Intact Anterior Cruciate Ligament in the Contralateral Knee and Rupturing the Anterior Cruciate Ligament Graft During the First 2 Years After Anterior Cruciate Ligament Reconstruction." The American Journal of Sports Medicine **35**(7): 1131-1134.

Zeller, B. L., J. L. McCrory, et al. (2003). "Differences in kinematics and electromyographic activity between men and women during the single-legged squat." Am J Sports Med **31**(3): 449-456.