The Relationship Between Dorsiflexion Range of Motion and Lower Extremity Movement Patterns and Muscle Activation

Elisabeth Corliss Macrum, LAT, ATC, CSCS

Thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Art in the Department of Exercise & Sport Science in the College of Arts & Sciences.

Chapel Hill
2008

Approved by:

Advisor: Darin Padua, PhD, ATC

Reader: Mike Lewek, PT, PhD

Reader: Michelle Boling, MS, ATC

Reader: David Bell, MEd, ATC

Reader: Chris Hirth, MS, ATC

ABSTRACT

Elisabeth Macrum: The Relationship Between Dorsiflexion Range of Motion and Lower Extremity Movement Patterns and Muscle Activation

(Under the direction of Darin Padua)

Objective: To determine the effect of induced gastrocnemius/soleus tightness on lower extremity kinematics and muscle activity. **Design:** Cross-sectional. **Subjects:** Healthy recreationally active subjects (n = 30, mean Height ±SD = 173.5 ± 12.1, Mean Weight ± SD = 72.0 ± 16.4). **Measurements:** Clinically measured dorsiflexion was assessed prior to collection of kinematic data. Participants performed five trials of an overhead squat with a 10 degree incline wedge placed under each foot (wedge condition) and without the wedge (no wedge condition). Three dimensional kinematics for the hip, knee, and ankle and electromyography of the VL, VMO, lateral gastrocnemius, and soleus were collected during the squatting tasks. Separate repeated measures ANOVAs were performed to determine differences in kinematics and EMG during the wedge and no-wedge conditions. **Results:** During the wedge condition, sagittal and frontal plane motion at the knee and muscle activity of the vastus medialis oblique, vastus lateralis, and soleus, were significantly different as compared to the no wedge condition. **Conclusion:** Based on our findings, limiting dorsiflexion range of motion leads to compensations at the knee and changes in muscle activity in the lower extremity that may have implications in overuse and acute knee injury.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Introduction:

Injuries in physically active populations most often occur in the lower extremity, with up to 42 percent of these injuries occurring at the knee (Hreljac 2003). Chronic knee pain, such as patellofemoral pain syndrome (PFPS) is one of the most common forms of knee overuse injury (DeHaven and Lintner 1986; Duffey, Martin et al. 2000; Taunton, Ryan et al. 2002; Hreljac 2003). PFPS is a term describing achy, diffuse pain surrounding the patella's articulation with the femur and presents itself in a variety of individuals from highly competitive athletes, to those involved in recreational activities. Symptoms of PFPS are usually exacerbated with activities which load the knee such as stair climbing, squatting, and sitting for extended periods of time (Loudon, Wiesner et al. 2002; Earl, Hertel et al. 2005). These symptoms include anterior knee pain, crepitus, and joint stiffness leading to a decrease in physical activity and difficulty performing activities of daily living. Anterior cruciate ligament (ACL) injury is one of the most common acute, catastrophic injuries at the knee, especially in athletic populations(Agel, Arendt et al. 2005). ACL injury and PFPS are commonly associated with similar risk factors (Powers 2003; Crossley, Cowan et al. 2004; Garrett and Yu 2007). Due to the consequences associated with PFPS and ACL injury, it is important to understand potential mechanisms predisposing an individual to PFPS or ACL injury to successfully prevent and rehabilitate these injuries.

Previous research on PFPS and ACL injury has examined a variety of lower extremity biomechanical variables to identify risk factors. Specifically, increased quadriceps angle (Q angle), has been linked to knee valgus position during dynamic activities and increased risk for PFPS and ACL injury (Moss, Devita et al. 1992; Powers 2003; Green 2005; Hewett, Ford et al. 2006; Piva, Fitzgerald et al. 2006). Several studies indicate that individuals suffering from PFPS demonstrate increased Q angle; however, this research has not been shown to be a risk factor for the development of PFPS (Boucher, King et al. 1992; Moss, Devita et al. 1992; Tang, Chen et al. 2001; Earl, Hertel et al. 2005). Increased Q angle and knee valgus positioning during activity are believed to facilitate PFPS by causing patellofemoral joint (PFJ) malalignment and periarticular irritation due to an increased lateral force on the patella via the association of the quadriceps musculature and iliotibial band with the lateral retinaculum (Moss, Devita et al. 1992; Green 2005). Increased Q angle is also generally associated with an increased risk for ACL injury (Powers 2003; Hewett, Ford et al. 2006). Altered activation of the vastus medialis oblique has also been theorized to contribute to PFPS (Cowan, Bennell et al. 2002; Mohr, Kvitne et al. 2003). Researchers theorize that decreased or delayed activation of the VMO in comparison to the vastus lateralis may lead to lateral patella tracking, which may facilitate the development of PFPS due to altered compressive forces at the PFJ (Souza and Gross 1991; Powers, Landel et al. 1996; Miller, Sedory et al. 1997; Cowan, Bennell et al. 2001).

Increased knee flexion angles are thought to increase compressive forces at the PFJ, possibly leading to PFPS in individuals who are involved in activities that use greater knee flexion angles. However, in samples with PFPS, decreased knee flexion has been observed during functional tasks, and is theorized to be a compensation as the quadriceps do not allow the flexion angles with highest PFJ pressures (Salsich, Brechter et al. 2001; Earl, Hertel et al. 2005). Decreased knee flexion angle during high-demand tasks has also been theorized to be a risk factor for ACL injury due to the relationship between decreased knee flexion and an increase in anterior tibial shear force (Garrett and Yu 2007; Sell, Ferris et al. 2007). Anterior tibial shear force is the primary force that loads the ACL, so having decreased knee flexion during high-demand tasks could put an individual at higher risk for injuring their ACL. While there are several lower extremity biomechanical variables that have been shown to differ between PFPS and healthy individuals it is not clear why differences in these biomechanical variables would develop.

Limited ankle dorsiflexion range of motion due to tightness of the gastrocnemius (Witvrouw, Lysens et al. 2000) and soleus (Piva, Goodnite et al. 2005) have also been reported in samples of individuals with PFPS. Piva et al. (2005) demonstrated that individuals with PFPS had significantly less flexibility of the gastrocnemius and soleus muscles in comparison to healthy controls. Similarly, Witvrouw et al. (2000) revealed decreased gastrocnemius flexibility in PFPS subjects compared to controls. Piva et al. (2005) describe a series of biomechanical compensations in those individuals with limited ankle dorsiflexion which may increase the risk for developing PFPS. Specifically, decreased ankle dorsiflexion during weight bearing tasks requiring an individual to lower their body's center of mass may cause increased subtalar joint pronation and tibial internal rotation to gain additional motion. Excessive tibial internal rotation is then theorized to increase femoral internal rotation and Q-angle / knee valgus position and ultimately result in greater patellofemoral contact pressure.

Limited ankle dorsiflexion ROM due to limited gastrocnemius and/or soleus muscle flexibility may also facilitate a change in knee flexion and quadriceps muscle activation. Greater knee flexion angles have been reported to occur when ankle dorsiflexion range of motion is limited, allowing the individual to successfully lower their body's center of mass (DiStefano LJ 2006). Increased knee flexion would require increased quadriceps activation to offset the increased external knee flexion moment and control the body's mass while being lowered (Salsich, Brechter et al. 2001; Earl, Hertel et al. 2005). The combination of increased knee flexion and quadriceps activation has been shown to increase patellofemoral contact pressures (Salsich, Brechter et al. 2001; Earl, Hertel et al. 2005), which may ultimately increase the risk for PFPS. Unfortunately, research has not been performed to determine the influence of limited ankle dorsiflexion on lower extremity kinematics and muscle activation patterns. To better understand the role of gastrocnemius and soleus muscle flexibility as potential risk factors for PFPS it is important to understand the influence of ankle dorsiflexion range of motion during weight bearing tasks on lower extremity kinematics and muscle activation variables that are believed to be risk factors for PFPS. Therefore the primary purpose of this study was to determine the effect of reduced dorsiflexion ROM on knee flexion angle, knee valgus angle, ankle dorsiflexion angle, hip flexion angle, quadriceps activation, gastrocnemius activation, and soleus activation during the descent phase of a squat task. The secondary purpose of this study was to investigate the relationships between gastrocnemius and soleus flexibility measures with these same dependent variables.

Independent Variables

- Wedge Condition
  - Wedge Condition
  - No Wedge Condition

Dependent Variables

- Criterion Variable
    - Clinically measured gastrocnemius dorsiflexion range of motion
    - Clinically measured soleus dorsiflexion range of motion
- Predictor Variables
    - Average/Peak EMG amplitude (EMG as a measurement in magnitude of activity) during the descending phase of the squat task
        - Soleus
        - Vastus Medialis Oblique
        - Vastus Lateralis
        - Gastrocnemius
    - Kinematic Variables
        - Start Values (knee flexion and valgus, hip flexion, ankle dorsiflexion)
        - Peak values during squat descent (knee flexion and valgus, hip flexion, and ankle dorsiflexion)
        - Range of Motion (ROM) values (knee flexion and valgus, hip flexion, and ankle dorsiflexion)
    - All kinematic and EMG variables measured and analyzed during the descending phase of motion of an overhead double leg squat.

Research Questions

- What is the effect of limited ankle dorsiflexion ROM during a double leg squat on the following dependant variables: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity?

- What is the relationship between gastrocnemius-limited dorsiflexion ROM as measured clinically and the following dependant variables: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity?
- What is the relationship between soleus-limited dorsiflexion ROM as measured clinically and the following dependant variables: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity?

Hypothesis

- Research:
    - Research Question #1: Peak knee valgus, peak knee flexion, and increased quadriceps activity, and decreased soleus and gastrocnemius activity will be significantly different under the wedge and no wedge conditions.
    - Research Question #2: Soleus-limited dorsiflexion ROM will have a positive relationship with peak functional dorsiflexion, and soleus activity and a negative relationship with peak knee valgus, peak knee flexion, quadriceps and gastrocnemius activity
    - Research Question #3: Gastrocnemius-limited dorsiflexion ROM will have a positive relationship with peak functional dorsiflexion, soleus and gastrocnemius activity, a negative relationship with peak knee flexion and knee valgus, and no relationship with quadriceps activity.
- Statistical:
    - Null:

  - Research Question #1: Limited ankle dorsiflexion ROM during an overhead squatting task has no effect on the following dependant variables: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity.
  - Research Question #2: There is no relationship between soleus-limited ankle dorsiflexion ROM and the following dependant variables during an overhead squatting task: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity.
  - Research Question #3: There is no relationship between gastrocnemius-limited dorsiflexion ROM and the following dependant variables during and overhead squatting task: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity.
- Alternative:
  - Research Question #1: Limited ankle dorsiflexion ROM during an overhead squatting task has an effect on the following dependant variables: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity.
  - Research Question #2: There is a relationship between soleus-limited ankle dorsiflexion ROM and the following dependant variables during

an overhead squatting task: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity.

- Research Question #3: There is a relationship between gastrocnemius-limited dorsiflexion ROM and the following dependant variables during and overhead squatting task: peak functional dorsiflexion, peak knee valgus, peak knee flexion, soleus activity, quadriceps activity, and gastrocnemius activity.

Operational Definitions

Functional dorsiflexion range of motion: The angle of the lower leg and foot segments with motion at the talocrural joint measured by kinematic data during the overhead squatting task.

Clinically measured gastrocnemius-dorsiflexion range of motion: The angle of the lower leg and foot segments with motion at the talocrural joint measured by goniometer at rest with the knee fully extended.

Clinically measured soleus- dorsiflexion range of motion: The angle of the lower leg and foot segments with motion at the talocrural joint measured by goniometer at rest with the knee flexed to 90 degrees.

Overhead Squat: Participants performed a squat with their feet shoulder-width apart and arms raised over their head. The participants squatted to a depth which was comfortable for them at a pace which enabled them to complete a set of seven consecutive squats.

Knee Valgus: Movement of the knee in the negative direction about the x-axis in the frontal plane.

Descending Phase of Motion: Motion from peak knee extension angle to peak knee flexion angle.

Dominant Limb: Lower extremity the subject would use to "kick a ball for maximum distance."

Surface Electromyographic Activity: Electromyographic activity using surface electrodes placements (Basmajian 1980; Cowan, Bennell et al. 2002).

No Wedge Condition: The subject will perform overhead squatting task on a flat surface in their own athletic shoes.

Wedge Condition: The subject performed the overhead squatting task with both feet on a slanted wedge (12 degrees from horizontal) to limit available dorsiflexion ROM.

Assumptions

- Sample used was indicative of a healthy general population
- Instruments used were reliable
- Subjects accurately reported medical history

Limitations

- Self-reported medical history
- Findings may not apply to individuals of other populations (ethnic regions, age, etc.)
- Findings may not apply to individuals with unaddressed lower extremity injury.
- EMG is not related to muscular contractile force.

Delimitations

- Subjects with history of lower extremity injury were excluded from study.

Significance of the Study

The current study served to examine a combination of lower extremity variables not previously examined in relationship to PFPS. The etiology of PFPS is not well understood, thus making the prevention and treatment of the condition difficult for clinicians. Findings of this study revealed compensations not previously observed, and may have implications in the clinical setting. Findings of this study in healthy individuals also formed a basis from which further research involving pathologic samples and other interventions could be performed.

CHAPTER 2

Introduction

The purpose of this study was to determine the effect of limited DF ROM on lower extremity muscle activity and kinematics to examine more deeply factors related to patellofemoral pain syndrome (PFPS). PFPS is described as anterior knee pain of unknown origin, which is exacerbated by loading of the knee such as in stair walking, squatting, and forceful motions such as jumping. Loading the knee results in increased compressive forces at the patellofemoral joint (PFJ) of up to 7 to 8 times body weight and a corresponding increase in symptoms (Fulkerson and Arendt 2000; Loudon, Wiesner et al. 2002; Tumia 2002). There are many biomechanical factors proposed to be associated with PFPS. These factors include both static and dynamic measures involving both soft tissue and bony anatomy. Many investigations in the area of PFPS have assessed frontal and transverse plane motions at the knee, foot, and hip (Moss, Devita et al. 1992; Earl, Hertel et al. 2005; Green 2005; Piva, Goodnite et al. 2005). There is some literature examining sagittal plane motion, however, it focuses mostly on how the hip relates to the knee. The little research done on sagittal plane ankle motion primarily focuses on factors during normal types of walking gait. This study will focus on the affects of static and dynamic alignments at the ankle joint on lower extremity muscle activity and kinematics.

Many people of different levels of activity suffer from PFPS. Despite much research surrounding PFPS, the etiology and treatment of this condition is not well understood. Many investigations have been performed to explore the relationship between frontal plane hip and knee motion and altered forces at the patellofemoral joint (PFJ). Additionally, the relationships between multiplanar motions at the foot and forces at the knee joint have also been investigated (Rose, Shultz et al. 2002; Levinger and Gilleard 2007; Joseph, Tiberio et al. 2008). These factors commonly studied in relation to PFPS can be described as static malalignments and dynamic risk factors. The purpose of this study is to determine the relationships between alterations in sagittal plane motion at the ankle, and compensatory motions and muscular activity seen at the knee and lower leg.

Relevant Anatomy

Understanding the functional anatomy of the lower extremity bony and soft tissue structures is important for understanding their effect on other structures throughout the kinetic chain. The area of direct importance is the patellofemoral joint (PFJ). This joint is the site at which signs and symptoms of PFPS will be observed. Other areas of importance for this investigation included the periarticular muscles of the knee joint, the tibiofemoral joint, true ankle joint (talocrural joint), and the subtalar joint.

The patellofemoral joint is where the posterior aspect of the patella articulates with the anterior aspect of the distal femur. The patella is the largest sesamoid bone in the body and is encased in the patellar tendon as it travels from the quadriceps to the tibial tuberosity on the anterior surface of the tibia. The patella serves to decrease friction and compressive forces at the patellofemoral joint by dispersing these forces over the femoral trochlea. Compressive forces at the patellofemoral joint are increased as the quadriceps group is activated and at increasing knee joint angles. If the quadriceps act abnormally or other PFJ stabilizing structures become dysfunctional, increased compressive forces over small contact areas can result in an increase in symptoms. The patella also serves as a pulley to lengthen the extensor mechanism of the quadriceps (Green 2005). Lengthening the extensor mechanism of the quadriceps creates a long lever arm, which decreases the force requirements for torque production at the knee as the quadriceps act in extension. The function of this joint as a pulley is even more important as the quadriceps control closed kinetic chain flexion during functional activities.

There are several structures thought to stabilize the PFJ during normal movement. These structures can be classified as static and dynamic in nature. Static structures stabilizing the PFJ refer to the lateral retinaculum, the bony congruency of the patella against the femoral trochlea, and the iliotibial band as it associates with the lateral retinaculum. Medially, the PFJ is statically stabilized by the medial retinaculum, and medial patellofemoral ligament. Dynamic stabilizers laterally include the vastus lateralis and sometimes the tensor fascia lata via the iliotibial band. Because of the lateral location of the iliotibial band and its association with the lateral patellar retinaculum, tightness in the iliotibial band is believed to cause altered patellar tracking (Earl, Hertel et al. 2005; Piva, Fitzgerald et al. 2006). Medially, dynamic stabilization is provided by the vastus medialis oblique, and adductor musculature due to their association with the medial retinacular tissue.

The bony anatomy of the patellofemoral joint is unique to its specific function. In the anterior-posterior view the patella appears as a rounded teardrop shape with the point (patellar apex) facing inferiorly. The base of the patella is the superior aspect which serves as the superior attachment site for the quadriceps tendon. The profile of the articular surfaces can be seen when the patella is observed in a superior-inferior view and has extremely thick cartilage along its surface (Grelsamer and Klein 1998). The two major patellar facets form a wedge shape with the larger, less angulated lateral facet and the more angulated facet on the medial side. These facets correspond to their given articular surfaces on the femur. The femoral trochlea, when viewed anterior-posteriorly, extends superiorly from the condyles of the femur which articulate with the tibia. The lateral side appears larger and extends more superiorly than the medial side. When viewing the trochlea superior-inferiorly, the two surfaces form a "V" the lateral surface protrudes anteriorly and is less angulated than the medial surface.

The ankle joints of importance to this study are the talocrural joint (true ankle joint) and the subtalar joint. The talocrural joint is formed by the dome of the talus as it fits between the malleoli (distal tibia and fibula) in the lower leg. Dorsiflexion and plantar flexion occur at the talocrural joint. All other motions considered to occur at the ankle occur at the subtalar joint or as a combination of motions at those joints. The subtalar joint is formed by the inferior aspect of the talus and the superior aspect of the calcaneus. Inversion and eversion occur at the subtalar joint, which can have implications in PFPS as these motions can cause rotations of the tibia that effect the PFJ (Piva, Goodnite et al. 2005). The tibiofemoral joint is essential to consider in this study as well as it is the primary joint where knee flexion and extension in the sagittal plane occurs. The distal femur articulates with the proximal tibia to form a hinge joint that allows some small degrees of tibial rotation in the transverse plane which is reported to affect the articulation of the patella on the femur. This transverse motion is believed to contribute to frontal plane motion at the knee during functional activity as knee valgus, which was of concern for this study.

Muscular anatomy important to this study includes the quadriceps, gastrocnemius and soleus musculature. The quadriceps group lies on the anterior aspect of the thigh and concentrically creates knee extension and hip flexion. The quadriceps musculature most important to this study includes the vastus lateralis and vastus medialis oblique. The vastus lateralis lies antero-laterally on the femur and acts as a dynamic lateral stabilizer of the PFJ. The vastus medialis oblique lies antero-medially and acts as the primary medial stabilizer of the PFJ. The quadriceps muscles come together at a common insertion through the quadriceps tendon to the superior aspect of the patella, and then travel to the tibial tuberosity via the patellar tendon.

The soleus is a deep plantar flexor of the ankle as it lies on the posterior aspect of the tibia and fibula, while the gastrocnemius lies superficially to the soleus. The soleus and gastrocnemius insert together on the posterior aspect of the calcaneus via the Achilles (calcaneal) tendon. The soleus, because of its origin on the posterior aspect of the tibia, only crosses the ankle joint, causing plantar flexion in open kinetic chain activity. The gastrocnemius, however originates at the distal aspect of the posterior side of the femur, crossing the knee and acting as a weak knee flexor as well as ankle plantar flexor. The gastrocnemius also has a medial and lateral head, thus, theoretically acting as medial and lateral stabilizers of the tibiofemoral joint. While performing closed kinetic chain activities, the soleus also acts to pull the tibia posteriorly to aid in knee extension during weight bearing as well as eccentrically control knee flexion and ankle dorsiflexion.

Differential Diagnosis:

Anterior knee pain can be classified as many different maladies and pathologies. These different pathologies can present very similarly and are often misdiagnosed. PFPS is described as anterior knee pain which is attributed to abnormal patellar movement in the patellofemoral joint due to static malalignments as well as dynamic factors (Messier, Davis et al. 1991; Lun, Meeuwisse et al. 2004; Earl, Hertel et al. 2005). Pain usually increases with loading and increasing shear forces as in stair walking, squatting, lunging, and deep knee flexing activities. Similar complaints are seen with other patellofemoral pathologies such as chondromalacia patella, patellar tendonitis/tendinosis, Osgood-schlatter disease, medial plica syndrome, and even iliotibial band tendonitis (Green 2005). These similar knee pathologies are similar in presentation, but different in which tissues are actually afflicted. It is imperative to properly identify which patellofemoral condition is present to properly treat the condition as their treatment courses commonly vary significantly.

There are currently a variety of theories on what tissues of the PFJ actually cause pain and become inflamed in individuals with PFPS. One theory is that degenerative changes in the articular cartilage irritate and cause inflammation in the synovial membrane of the joint capsule surrounding the PFJ (Green 2005). Other vague descriptions involve variations of irritation to soft tissue structures in and around the PFJ (Green 2005).

Static Malalignments:

Many factors have been examined in relation to PFPS, including static and dynamic factors. Static measures have been studied at the hip, knee, and foot and the effect those factors have on the patellofemoral joint. Static malalignments of concern in the current literature include quadriceps angle, and lower extremity musculature tissue extensibility/flexibility.

The quadriceps angle (Q angle) is described in the literature as the angle formed by the line between the anterior superior iliac spine (ASIS) and the mid point of the patella, and the line from the mid point of the patella to the tibial tuberosity (Moss, Devita et al. 1992; Green 2005; Piva, Fitzgerald et al. 2006). The angle that is formed by the intersection of these two lines represents the angle of pull of the quadriceps musculature on the patella. Normative values for men and women differ and have been reported in the literature as 10 degrees and 15 degrees, respectively (Green 2005). The greater normative value for women is due mainly to the differing pelvic anatomy in their wider innominate bony make-up compared to their male counterparts. Wider innominate structure in females results in a greater lateral placement of the ASIS in relation to the center of the patella, thus widening the Q angle. Researchers have found that a Q angle greater than 17 degrees may predispose an individual to PFPS (Messier, Davis et al. 1991; Moss, Devita et al. 1992). This value may not be generalized to the entire physically active population, however, because it was found in a group of high school female athletes from differing sport backgrounds. Other studies have mentioned theoretical links between increased Q angle and PFPS (Messier, Davis et al. 1991; Tang, Chen et al. 2001).

It is difficult to compare Q angle values from different studies as there is no true standard in measurement method. For a static measurement, it is commonly measured while lying supine or standing. Standing measurement is thought to be more reliable and functional as it places the individual in a normal functional position. Taking the Q angle measurement standing with out footwear has also been performed in the literature as pronation increases Q angle (Green 2005).

Studies which have examined Q angle as a predictor for PFPS have found a correlation between greater Q angle and presence of PFPS, but many researchers questions is true significance conflict over its true importance (Tang, Chen et al. 2001; Green 2005). Excessive Q angle is generally considered an important risk factor as it increases lateral patellar tracking, which is considered as the greatest risk factor for PFPS as it changes the dispersement of compressive forces at the patellofemoral joint.

Other static malalignments commonly studied in populations with PFPS concern extensibility and flexibility of muscular tissue. Muscles and their associated connective tissue of primary concern in the literature are the tensor fascia lata, quadriceps, hamstrings, and the gastrocnemius/soleus group. The flexibility of the gastrocnemius/soleus group has been studied, but not compared to other common factors (Witvrouw, Lysens et al. 2000; Hreljac 2003; Green 2005; Piva, Fitzgerald et al. 2006).

Most of the research on soft tissue extensibility in relation to PFPS has been performed in relation to the tensor fascia lata and its long tendinous attachment, the iliotibial band. Because of the lateral location of the iliotibial band and its association with the lateral patellar retinaculum, tightness in the iliotibial band is thought to cause altered patellar tracking in the patellofemoral joint (Earl, Hertel et al. 2005; Piva, Fitzgerald et al. 2006). If the tensor fascia lata is hyperactive or tight, it can cause a restriction distally at the iliotibial band and lateral patellar retinaculum. Tensor fascia lata hyperactivity has been suggested as a compensatory finding due to underactive gluteus medius musculature due to an increase in internal rotation of the femur (Green 2005). A tight iliotibial band was also a proposed factor in increased femoral internal rotation which can cause altered patellar tracking and PFPS (Green 2005).

The quadriceps muscle group has been investigated extensively in relation to onset and amount of activation. Little has been done in respect to its extensibility. Some research suggests that limited quadriceps flexibility correlated with PFPS (Smith, Stroud et al. 1991; Witvrouw, Lysens et al. 2000). This is seen in a study which observed elite figure skaters and found that the skaters, both males and females who had PFPS had significantly less quadriceps flexibility than those who had no injury or those who had other knee pathologies (Smith, Stroud et al. 1991). In another study which examined risk factors for PFPS prospectively, decreased quadriceps flexibility was found in subjects who developed PFPS compared to those who did not (Witvrouw, Lysens et al. 2000).

Hamstring flexibility has also been studied as a risk factor for PFPS. Due to the hamstrings attachment to the proximal tibia, and their action in flexing the knee, they may cause alterations in contact pressures at the PFJ. Tight hamstring musculature may lead to a hyperactivity of the quadriceps which may lead to increased contact pressure at the PFJ. Restricted hamstrings flexibility may cause slight postural knee flexion, which has been associated with PFPS (Fulkerson and Arendt 2000). In the same elite figure skaters studied for quadriceps flexibility, it was shown that the individuals with PFPS also had significantly decreased hamstring flexibility (Smith, Stroud et al. 1991). Hamstrings length testing as a predicting factor for PFPS was also found to be a reliable measure (Piva, Fitzgerald et al. 2006).

Gastrocnemius and soleus extensibilities are mentioned in the literature as having a significant relationship with PFPS (Witvrouw, Lysens et al. 2000; Hreljac 2003; Green 2005; Piva, Fitzgerald et al. 2006). In a review of literature, on researcher made mention of decreased ankle dorsiflexion causing compensatory motions at the foot and knee possibly leading to PFPS (Green 2005). Compensatory motions theorized to result from decreased dorsiflexion include increased knee flexion, increased knee valgus and increased foot pronation. Gastrocnemius and soleus length, tested together, were also found to be strong predictors of PFPS (Piva, Fitzgerald et al. 2006). There is speculation of how this decreased gastrocnemius and soleus length may lead to the development of PFPS, but little to no research supports this.

Dynamic Risk Factors:

Dynamic risk factors have been researched intensely in an attempt to better understand the etiology of PFPS. Dynamic factors can potentially be more valid because they mimic a more active environment in which the stresses placed across the patellofemoral joint may be greater. Dynamic biomechanical risk factors in the literature include functional Q angle, tibial rotation, hip internal rotation, pronation, knee flexion, and ankle dorsiflexion. Other dynamic risk factors consist of muscular imbalances of the stabilizers, and gross movers. Muscular imbalances include decreased flexibility, altered activation levels, and/or muscle weaknesses.

Dynamic Q angle is a measurement theorized to take into account tibial and hip rotation, and hip adduction (Moss, Devita et al. 1992). Dynamic Q angle is simply the measurement of Q angle through kinematic analysis of motion. Researchers have reported significant differences in static Q angle between control and PFPS subjects (Moss, Devita et al. 1992). Additionally, decreased Q angle values have been reported in patients with PFPS compared to controls at maximum pronation during walking. This may be due to the control and pathologic groups reaching maximum functional Q angle at different times during gait (Moss, Devita et al. 1992).

Subtalar joint pronation is also theorized as a risk factor for PFPS due to the effects it has up the kinetic chain. Pronation has been considered a contributory factor to increased Q angle as standing bare-foot has shown to increase this angle as it causes tibial internal rotation on the femur, which is a component of this motion (Holmes and Clancy 1998; Gross and Foxworth 2003). Some researchers have tested the effects of foot orthotic use in aiding PFPS and the risk factors associated with it. Rose et al. tested acute orthotic use to determine its affect on measures of functional Q-angle. They reported no clinically significant changes compared to barefoot trials (Rose, Shultz et al. 2002). Other researchers have speculated through subject measures such as reported pain and observable gait changes, there appears to be some relief of PFPS with orthotic use. This relief of pain is theorized to be due to improvement of Q angle and thus decreasing the compressive forces at the patellofemoral joint (Gross and Foxworth 2003). Subjects with subtalar joint pronation were also found to have a greater time to maximal pronation during walking suggesting that they pronate during a greater amount of their gait than the control group (Moss, Devita et al. 1992). Because pronation is commonly thought to increase Q angle and lateral patellar tracking, longer times in pronation can cause greater time with altered contact pressures at the PFJ.

Knee flexion range of motion is commonly investigated as a static measure of quadriceps flexibility, but there has been some research on knee flexion during functional tasks. Decreased knee flexion was found in a group with PFPS when compared to the control group in a single leg squat without concern for ankle range motion. This decrease in motion may be due to muscular guarding due to pain in the patellofemoral joint. One group of researchers found a decreased knee extension moment (net quadriceps force) in the pathological group when compared to the control which was described as a ”quadriceps-avoidance” strategy (Salsich, Brechter et al. 2001). Another group of researchers also found decreased contact and peak knee flexion angles in a PFPS group compared to control during stair ambulation (Crossley, Cowan et al. 2004).

Another proposed factor influencing knee flexion is sagittal plane ankle range of motion. It has previously been reported that restricting ankle plantar flexion causes an increase in knee flexion angle during a jump-landing task (DiStefano, In Press). If an individual has decreased ROM at the ankle joint, he or she may compensate for this decreased motion through increased flexion at the knee when required to squat to the same depth. The increased knee flexion increases the compressive forces at the patellofemoral joint and may ultimately lead to the development of PFPS. Based on these findings ankle dorsiflexion motion during functional activity may have an influence on the motions occurring throughout the kinetic chain.

Normative values for dorsiflexion clinically are usually centered about a single value; however motion should be presented in a range as there are individual differences and differences in instrumentation and measurement techniques between clinicians. There is also little information in the literature concerning dorsiflexion range of motion and what is adequate for proper function in activity. Researchers in one study reported significantly greater dorsiflexion values in the same subjects using a weight-bearing method versus non weight-bearing method (Baggett and Young 1993). These researchers found greater dorsiflexion values when the subjects dorsiflexed with the foot on the ground, than with clinician-induced passive force into dorsiflexion.

Dynamic risk factors studied at great length in the PFPS population also include muscular activity. The quadriceps musculature have been investigated in EMG activity, onset and magnitude extensively in respect to the hamstrings and also with respect to itself as it is often broken down into vastus medialis oblique versus vastus lateralis. Quadriceps and hamstrings are generally studied in conjunction due to their agonist/antagonist relationship.

When the quadriceps are broken down and examined, the most common comparison is performed between the vastus medialis oblique and the vastus lateralis. These two muscles are thought to have agonist/antagonist patellar stabilizing roles. The vastus medialis oblique is thought to have a medial stabilizing role due to its medial placement and association with the medial connective tissue and retinaculum surrounding the patella and the oblique orientation of its fibers. The vastus lateralis, conversely, stabilizes laterally due to its lateral placement and association with the lateral retinaculum and iliotibial band. Current thought in the literature on the differences seen between these muscles is in onset of activation, magnitude of activity, and during what types of activity these respective muscles are more active. Researchers in one study found that there was no significant difference between a PFPS group and control group in time of vastus medialis oblique onset versus vastus lateralis onset (Cowan, Bennell et al. 2001). In another study using a similar design there was still no significant difference in vastus medialis oblique and vastus lateralis activity onset or amplitude in the PFPS versus the control group. The researchers did find, however, that over time there was a decreased level of activity of the vastus medialis oblique in the PFPS group during various types of walking indicating a possible difference in need of further evaluation (Powers, Landel et al. 1996). Still, more researchers found that while observing PFPS subjects versus control subjects in a closed kinetic chain exercise, the two groups approached statistically significantly increased vastus lateralis activity compared to the vastus medialis during closed kinetic chain activity (Miller, Sedory et al. 1997). Researchers have also compared VMO and VL activation in patients with PFPS and control subjects during an isotonic and isometric contraction.

Soleus activity has been studied at length, but not generally in the PFPS population. Most data on the soleus currently in the literature compares it to properties of the gastrocnemius and indicates its role in controlling posture (Hodgson 1983; Romano and Schieppati 1987; Kavounoudias, Roll et al. 2001). Through EMG analysis of cats, some researchers concluded that of the major plantar flexors of the ankle, the gastrocnemius primarily served to plantar flex the ankle forcefully, producing power, whereas the soleus served in more postural control (Hodgson 1983). Other researchers who used human subjects found increased soleus activity during balance activities to correct anterior sway (Kavounoudias, Roll et al. 2001). This finding could be similar to eccentrically controlling dorsiflexion during functional tasks. Little is known about the soleus in relation to quadriceps activity or ankle range of motion.

Dynamic risk factor information seems to be more readily sought than static measures in comprehending the risk factors for PFPS in an active population. Although this is more applicable as the factors observed are functional, they may not all be clinically relevant. Many studies are designed without the clinician in mind. Current research has looked at a variety of variables in multiple planes to gain more knowledge about the origin of PFPS. There has been little research looking purely at sagittal plane motion restrictions at the ankle and how they might affect motion up the kinetic chain. The current study is designed to bring in clinically relevant measures with lab techniques to determine the relationship between decreased dorsiflexion and soleus and quadriceps activation, and three-dimensional kinematics at the knee. This will serve to enable clinicians to know how the clinical measures they may use in their practice correlate alterations in movement patterns up the kinetic chain.

CHAPTER 3

Subjects

Subjects who participated in this study were healthy, asymptomatic, and ranging in age from 18 to 30 years old. Thirty subjects completed the test protocol (15 m, 15 f, height = 173.5 ± 12.1cm, weight = 72.0 ± 16.4kg). Mean soleus-limited dorsiflexion was 10.9 degrees ± 4.9 degrees. Mean gastrocnemius-limited dorsiflexion was 1.7 degrees ± 4.5 degrees. All subject demographic information can be found in Table 1. The subjects were recruited from the general student and faculty/staff populations at the University of North Carolina at Chapel Hill (UNC-CH) via informational flyers posted across the campus and verbal recruitment by the study principal investigator (EM). For inclusion in the study, subjects were determined to be physically active, which was defined as 30 minutes of physical activity a day for a minimum of 3 days a week. Additionally, subjects must have had current or former participation, at least one year of high school or college varsity, in organized soccer, volleyball, basketball or lacrosse. Subjects were excluded if they reported lower extremity injury in either leg within the past 3 months that caused them to not participate in physical activity for at least one day or required physician referral. Subjects who reported lower extremity surgery within the past year or who had current knee pain at time of testing session were also excluded from this study. Prior to study participation all subjects completed a questionnaire regarding their inclusion / exclusion criteria status and signed an informed consent form approved by the Institutional Review Board.

Instrumentation

A universal 12-inch goniometer was used to measure passive ankle dorsiflexion range of motion (ROM) at 0° and 90° of knee flexion. Electromyographic (EMG) data were collected using the Delsys Bagnoli-8 Non-telemetered system (Delsys, Inc. Boston MA). Unit specifications included a CMRR of 92 dB and amplifier gain of 1000. EMG data was collected at 1200 Hz. Kinematic data was obtained using 7 Vicon MX-40 Infrared Cameras at a rate of 120 Hz (Vicon Motion Systems, Lake Forest, CA). Calibration volume for the Vicon MX-40 Infrared Cameras was 2.5 m long /x 1.5 m wide x 2.5 m high. All kinematic and EMG data were collected using the Nexus software (version 1.0) (Vicon Motion Systems, Lake Forest, CA).

Testing Procedures

Subjects reported to the Sports Medicine Research Laboratory for a single testing session lasting approximately 1 hour. Subjects read and signed an informed consent for the study prior to performing data collection. The researcher reviewed the inclusion and exclusion criteria, procedures, and any possible positives and/or negatives to their involvement in the study, and the subject was given an opportunity to ask any questions he or she may have had regarding the study prior to the start of data collection. The subjects were required to wear standard running shoes, spandex shorts, and a spandex t-shirt or sports bra. Data from the subject's dominant leg was used for all data analyses and the dominant limb was defined as the leg used to kick a ball for maximal distance.

Prior to subject set-up and data collection the subject warmed up on a stationary cycle ergometer (Schwinn Airdyne Upright Bike, Nautilus, Inc.) for 5 minutes at a self-selected pace. Flexibility of the gastrocnemius and soleus muscles was assessed by measuring the amount of passive ankle dorsiflexion range of motion. Gastrocnemius and soleus flexibility were measured in a counterbalanced order. Gastrocnemius muscle flexibility was measured with the knee positioned in 0° of flexion with the subject in the long sitting position. Soleus muscle flexibility was measured with the knee positioned in 90° of flexion with the subject sitting on the edge of a treatment table. During both gastrocnemius and soleus flexibility measures, the principal investigator passively dorsiflexed the subject's ankle until the point of soft tissue resistance while maintaining the subtalar joint neutral position by palpating the medial and lateral aspect of the talar head. Ankle dorsiflexion angle was measured with a standard goniometer as the angle formed by the shaft of the fibula (line drawn from fibular head to lateral malleolus) and the lateral midline of the foot (line drawn along the border of the rearfoot / calcaneus and base of fifth metatarsal) (Piva, Fitzgerald et al. 2006). This was repeated three times each for gastrocnemius and soleus flexibility measures. The arithmetic mean of each position was recorded and used for data analysis. Intra-rater reliability for soleus ($ICC_{2,k}$= 0.84, SEM= 2.03) and gastrocnemius ($ICC_{2,k}$= 0.86, SEM= 1.68) range of motion was established to be good prior to the beginning of the study.

Following range of motion measurements the subject was prepared for EMG and motion analysis data collection. Each subject's skin was shaved and cleaned with gauze and isopropyl alcohol prior to application of surface electrodes. Surface EMG electrodes were attached over the vastus medialis oblique (VMO), vastus lateralis (VL), soleus (SOL), and lateral gastrocnemius (LG) musculature. The electrodes for the quadriceps were placed over the VL, approximately 10cm superior and 7 cm lateral to the superior border of the patella oriented at 10 degrees to the vertical (Cowan, Bennell et al. 2002). For the VMO the electrode were placed approximately 4 cm superior and 3 cm medial to the superomedial border of the patella oriented at a 55 degree angle(Cowan, Bennell et al. 2002). The electrode for the LG was placed over the bulge of the lateral head of the gastrocnemius (Basmajian, Blumenstein, and Dismatsek, 1980). Electrode placement for the SOL was placed just medial to the medial aspect of the achilles tendon, inferior to the midpoint of the lower leg (Basmajian, Blumenstein, and Dismatsek, 1980). A reference electrode was placed over the tibial tuberosity of the test limb. All electrode placements were reinforced with pre-wrap and athletic tape and were verified and checked for cross-talk with manual muscle testing prior to moving on with data collection.

Before each testing period, the data collection volume for kinetics and kinematics was calibrated. Reflective markers were attached bilaterally to subjects on the following landmarks: L5-S1 space, ASIS, greater trochanter, medial and lateral femoral epicondyles, mid-thigh, mid shank, medial and lateral malleoli, head of the 5th metatarsal, head of the first metatarsal, calcaneus, and acromion process. All markers were placed over clothing or footwear if they could not be applied directly to the skin at a given landmark. Prior to trial data collection data, static trials were performed with the subjects facing in the positive-x axis direction, feet shoulder-width apart, and both arms abducted to 90 degrees. Medial malleolus and medial femoral condyle markers were removed from both legs prior to beginning trial data collection.

Three-dimensional (3-D) videographic and electromyographic data were collected for each subject as they performed a series of double leg squats. A global reference system was defined using a right hand coordinate system, in which the x-axis was positive in the anterior direction, the y-axis was positive to the left of each subject, and the z-axis was positive in the superior direction.

Subjects performed seven double leg squat trials under two separate conditions: a no-wedge condition with the foot positioned flat on the floor, and a wedge condition with a 12° forefoot angle. The wedge ran along the full length of the foot. The forefoot portion of the wedge was 12° relative to the hindfoot and the medial and lateral aspects of the wedge were at a 0° relative to each other. The wedge was designed to place the subject's ankle in 12° of ankle dorsiflexion while in the upright position before performing the double leg squat task, thereby minimizing the amount of dorsiflexion motion during the double leg squat. A 12° wedge was determined through pilot testing to cause a change in kinematics, but not make the task impossible to perform. The order in which the test conditions were performed was counterbalanced.

During the squat task, the subject was instructed to perform a double leg squat "as if they are sitting back in a chair" with their arms overhead while keeping them in line with their ears, and heels on the floor. The subject's feet were positioned shoulder-width apart, with their feet facing forward (toward positive x). The subject was instructed to squat to a depth as far as they were comfortable. The subject was allowed a maximum of five practice repetitions and was provided two minutes of rest between the practice and test trials. Subjects performed seven test repetitions per trial period with one minute rest between the sets. The two sets consisted of one set of the no wedge and one set of the wedge condition. The middle five trials were used for data reduction and statistical analysis. EMG measurements were analyzed in the descending phase for mean amplitude of activity during the overhead squat. Kinematic data collected included peak knee flexion angle, peak ankle dorsiflexion angle, peak hip flexion angle, and peak knee valgus angle.

After all repetitions of the test trials were performed, maximal voluntary isometric contractions (MVICs) were performed for normalization of the EMG data. Subjects performed 3 trials for each MVIC. The mean of the middle 3 seconds of each trial were used to find the total arithmetic mean for normalization of the EMG data. MVIC's were performed for the VMO, VL, LG, and SOL musculature. For VMO and VL MVIC's, the subject was seated in a dynamometer chair with knees and hips flexed to 90 degrees and was instructed to "kick out" against the resistance of the strap to extend the knee and for five seconds. Soleus and gastrocnemius MVICs were collected using a nylon strap across the metatarsal heads (ball of foot) of the test side. Soleus MVIC was collected with the subject in a quadriped position with knees and hips flexed to 90 degrees on the table with a strap around the heads of the metatarsals of the test limb. Gastrocnemius MVICs were collected with the subject lying prone with the test limb off the end of the table and the strap across the metatarsal heads. For both the soleus and gastrocnemius MVICs, the subjects plantar flexed against the strap with maximal effort.

Data Processing and Reduction

EMG mean amplitude of the quadriceps, gastrocnemius and soleus were normalized to the maximum voluntary isometric contraction for each subject. Mean amplitude measures were calculated for quadriceps, gastrocnemius and soleus for the descending phase. Descending phase was defined as the onset of motion through peak knee flexion angle (Figures 1-4). Peak knee flexion was defined as greatest knee flexion angle reached by the subject during the task. Peak knee valgus angle was defined as the peak frontal plane motion of the knee toward the midline. Peak ankle dorsiflexion angle was defined as the greatest point of dorsiflexion angle through each phase of the task. All data were imported into

Motion Monitor Software (version 7.72) (Innovative Sports Training, Inc. Chicago IL). A custom MatLab program was used to determine kinematic variables during the squatting task (Mathworks, Natick MA). EMG data were filtered with a bandpass filter between 10 and 350 Hz using 4^{th} order Butterworth filter. EMG data were further smoothed by taking the root mean square over a 20 ms time constant. Kinematic data were also filtered at 12 Hz using a 4^{th} order Butterworth filter with a 12 Hz cut off frequency.

Statistical Analyses

All data analyses were performed using SPSS version 13.0 (SPSS, Inc. Chicago, IL). Pearson product moment correlations were performed to determine the relationship between gastrocnemius and soleus flexibility measures and each of the following dependent variables: peak angles during the descent phase of ankle dorsiflexion, knee valgus, knee flexion and hip flexion, as well as mean soleus activity, quadriceps activity, and gastrocnemius activity. Separate repeated measures ANOVAs were run for each: mean EMG amplitude for quadriceps, gastrocnemius, and soleus, and start angles, peak angles, and ROM values for ankle dorsiflexion, knee valgus, knee flexion, and hip flexion during the descent phase of the squat. The within subject factor was wedge condition (2 levels: wedge, no wedge). A priori alpha level was set at 0.05.

CHAPTER 4

Thirty subjects completed the test protocol (15 males and 15 females). Mean height was 173.5 cm ± 12.1 cm. Mean weight was 72.0 kg ± 16.4 kg. Mean soleus-limited dorsiflexion was 10.9 degrees ± 4.9 degrees. Mean gastrocnemius-limited dorsiflexion was 1.7 degrees ± 4.5 degrees. All subject demographic information can be found in Table 1.

We observed a significant decrease in peak knee flexion angle when the overhead squat was performed on the wedge ($F_{(1, 27)}$=105.5, $p \leq 0.001$) (Table 3). We also observed a significant decrease in knee flexion range of motion during the wedge condition ($F_{(1, 27)}$=90.6, $p \leq 0.001$) (Table 4). This decrease in knee flexion during the wedge condition was coupled with a significant increase in peak knee valgus angle ($F_{(1, 27)}$=6.6, p=0.02) (Table 3). Knee valgus ROM also significantly increased during the wedge condition ($F_{(1, 27)}$=2.1, p=0.02) (Table 4).

We observed significant changes in motion at the ankle as well. The ankle dorsiflexion start angle was significantly increased with the wedge condition ($F_{(1, 27)}$=3.0, $p \leq .001$) (Table 2). Participants also went through significantly less ankle ROM with the wedge in place ($F_{(1, 27)}$=158.3, $p \leq .001$) (Table 4). There was a significant difference in peak ankle dorsiflexion as participants reached a greater amount of dorsiflexion with the wedge in place ($F_{(1, 27)}$=7.4, p=0.01) (Table 3). Clinically measured dorsiflexion ROM (knee extended and knee flexed) did not correlate with any dependent variable (Table 6).

We observed significant changes in the soleus and quadriceps muscle activation. Soleus activity increased during the descent phase when the squat was performed on the wedge ($F_{(1, 27)}$=4.2, p=.049). However, when we examined quadriceps activity both the VL and the VMO significantly decreased with the wedge condition during the descending phase (VL: $F_{(1, 27)}$=12.2, p=0.002; VMO: $F_{(1, 27)}$=5.6, p=0.03) of the squat. We observed no differences in gastrocnemius EMG amplitude for the two squat conditions for the descending ($F_{(1, 27)}$=1.7, p=0.21) phase (Table 4).

CHAPTER 5

The finding of key importance in this study was that knee valgus increased when the overhead squat task was performed on the wedge. We hypothesized this would occur because the wedge would lead to compensations at the knee and/or hip due to the decreases in available ankle range of motion. Our results support this hypothesis and provide further support that restrictions in ankle motion (in this case with the wedge in place) alters kinematics up the kinetic chain.

Participants in this investigation increased their knee valgus angle by approximately one degree when sagittal plane ankle range of motion was limited with the wedge. While the increase in knee valgus angle during the wedge condition was small in absolute magnitude (1º increase) this represented an overall increase in knee valgus angle of 16% during the wedge condition compared to the no wedge condition. Given the smaller available range of knee valgus motion in comparison to knee flexion we feel that this statistically significant increase in knee valgus angle is clinically important. Previous research has reported that similar increases in knee valgus angle (1-2º increase) can lead to an increased risk of injury (Joseph, Tiberio et al. 2008). Other research has shown that placing a wedge under the heel to increase the starting plantar flexion angle and allow for greater ankle dorsiflexion motion during a squat caused a decrease in medial knee displacement as compared to performing a squat without the wedge (Bell, In Press). The findings from this investigation along with our study highlight the influence of ankle dorsiflexion range of motion on knee valgus motion during tasks that involve a squatting motion.

We also demonstrated that limiting the amount of available ankle dorsiflexion range of motion during the wedge condition resulted in a concomitant decrease in peak knee flexion angle and range of motion. Peak knee flexion angle decreased by approximately 17º during the wedge condition compared to the no wedge condition. Interestingly, this large change in knee flexion angle represented a 16% decrease in knee flexion, which is identical to the percent increase in knee valgus angle. We hypothesize that limited ankle dorsiflexion range of motion during the wedge condition resulted in an inability to achieve full knee flexion (16% decrease) which resulted in a compensatory increase in knee valgus angle (16% increase) as the individual attempted to lower their body's center of mass during the squat motion. We did not observe any changes in hip flexion motion during the wedge condition, which suggests that squat kinematic alterations during the wedge condition are most readily apparent at the knee (decreased knee flexion and increased knee valgus).

Ankle dorsiflexion range of motion significantly decreased by 8º during the wedge condition, which represents a 27% decrease in motion compared to the no wedge condition. This indicates that the wedge did, in fact, limit dorsiflexion as we hypothesized it would, and the compensations seen at the knee are likely due to limited ankle dorsiflexion motion. We hypothesize that the restrictions created in ankle dorsiflexion motion during the wedge condition caused the obligatory compensations of decreased knee flexion angle and increased knee valgus angle.

The compensatory changes associated with limiting ankle dorsiflexion motion may have considerable clinical relevance as decreased knee flexion and increased knee valgus have been implicated as body postures associated with increased risk of PFPS and ACL injury (Messier, Davis et al. 1991; Moss, Devita et al. 1992; Malinzak, Colby et al. 2001; Crossley, Cowan et al. 2004; Hewett, Ford et al. 2006). Increased knee valgus has been implicated as a risk factor in PFPS due to the forces which subsequently occur at the PFJ. Pathologic samples have shown knee valgus positions just two degrees greater than those of symptom free samples (Moss, Devita, 1992). This increase in knee valgus is often associated with tightness of the IT band and a lateral tracking of the patella in the PFJ (Earl, Hertel et al. 2005; Green 2005; Piva, Fitzgerald et al. 2006). This malalignment of the patella can cause an increase in contact pressure over a smaller area of the lateral surface of the femoral trochlea and an increase in tensile force on the medial stabilizing structures (Pangiotopoulos, et al 2005). This alteration in contact stresses are theorized to lead to the development of PFPS (Powers 2003). Increased knee valgus has been implicated as a risk factor for ACL injury in the literature through its association with increased Q angle (Powers 2003; Hewett, Ford et al. 2006).

Decreased knee flexion angle has also been implicated in injuries at the knee. Flexibility measures of the quadriceps have been shown to be decreased in subjects suffering PFPS, possibly as compensation for other kinematic variations or for avoidance of pain (Piva, Fitzgerald et al. 2006). Additionally, decreased knee flexion angle during dynamic tasks in individuals with PFPS has been reported by several researchers (Salsich, Brechter et al. 2001; Crossley, Cowan et al. 2004). Decreased knee flexion during higher-demand tasks has also been connected with increased risk of anterior crutiate ligament (ACL) injury because of its association with increased anterior tibial shear force. Anterior tibial shear force is the primary force which loads the ACL, so having a decreased knee flexion angle during dynamic activities such as jumping, running and cutting may predispose an individual to an ACL injury(Garrett and Yu 2007; Sell, Ferris et al. 2007). Furthermore, recent research has purported that females are at higher risk for ACL injury (Agel, Arendt et al. 2005; Mihata, Beutler et al. 2006) because females tend to have decreased knee flexion angles during high demand functional tasks such as cutting or jump-landing maneuvers when compared to their male counterparts (Malinzak, Colby et al. 2001; Chappell, Creighton et al. 2007). We hypothesize that these changes in kinematics seen with limited ankle dorsiflexion may load the PFJ and ACL similarly and potentially result in increased risk of injury to these structures. We did not examine joint loading in this study, but this should be examined in future research.

Previous research also supports the concept that decreased ankle dorsiflexion motion may be a risk factor for lower extremity injury. Gastrocnemius and soleus flexibility deficits have been reported in samples of individuals with PFPS (Piva, Fitzgerald et al. 2006, Green 2005). We speculate that decreased knee flexion and increased knee valgus seen were a function of the limited available dorsiflexion in our study, which may imply that the gastrocnemius and soleus flexibility deficits seen in pathologic samples may be a precursor, and not compensation to PFPS. The compensations seen in this study are commonly speculated to be related to PFPS and ACL injury, which may indicate that decreased range of motion at the ankle may also play a role in making individuals more susceptible to overuse or acute injury at the knee.

Limiting ankle dorsiflexion during the squatting task resulted in decreased activity of the quadriceps musculature and increased activity of the soleus during the descent phase of the squat. These changes are likely due to the changes observed in knee flexion and ankle dorsiflexion kinematics during the wedge condition. As previously indicated there was a significant decrease in peak knee flexion angle and range of motion during the wedge condition, which most likely accounts for the decrease in quadriceps (VMO and VL) muscle activity. Quadriceps activation is necessary during the descent phase of the squat to control knee flexion motion and prevent the knee from collapsing in the sagittal plane. By restricting the amount of knee flexion motion during the wedge condition less quadriceps activity was required. Soleus muscle activation was significantly increased during the descent phase of the squat task even though there was a significant decrease in ankle dorsiflexion range of motion during the wedge condition. While ankle dorsiflexion range of motion was decreased the peak ankle dorsiflexion angle was slightly increased during the wedge condition. Thus, we believe that greater soleus activation was required during the wedge condition to control the larger ankle dorsiflexion angle as the soleus acts to eccentrically resist ankle dorsiflexion motion. Gastrocnemius activity remained unchanged, possibly due to its diarthodial nature. During the squatting task, at both ends of the motion, one joint attempts to shorten the gastrocnemius while the other lengthens it, causing it to play no significant role in the control of the knee or ankle motion.

This study had several limitations. Squat depth and cadence were not controlled because we wanted to observe “natural” movement pattern compensations imposed by the wedge. Future research should consider controlling for these variables to see how they may differ from the outcomes observed in this study. A second limitation of the study is the wedge itself. There might be changes caused by the wedge that we did not consider and these changes may explain results such as alterations to center of mass. However, given that this is the first study concerning this combination of variables, we felt this was an appropriate intervention. Additionally, performing a squat on a wedge is not a realistic situation. Future research in this area should use an intervention which enables the foot to remain in a locked but functioning position, using a brace technique or other device limiting sagittal motion at the ankle. The position of the wedge in the test area was also not controlled by the principal investigator. An additional analysis was performed to determine if there was a significant difference in the foot placement between the wedge and no wedge conditions. We found there was a significant difference between conditions ($F_{(1, 27)}=5.31$, $p=0.029$) with the feet being 2-cm farther apart during the no-wedge condition compared to the wedge condition. Although this finding was significant, we speculate that this did not influence the results of this investigation. Future investigations should control for the distance between feet to ensure that changes in kinematics are not due to subject positioning.

Clinically, these findings may suggest that the natural compensation to gastrocnemius and soleus tightness is decreased sagittal plane motion and increased frontal plane motion at other joints up the kinetic chain. Over time this may lead to other imbalances throughout the kinetic chain, making the individual more susceptible to overuse or acute knee injuries such as PFPS or ACL injury. Most research has assessed static alignment issues at the foot, and hip muscle imbalances in relation to PFPS, but few have considered the ankle joint. This study suggests that, for at least a portion of individuals, restrictions in available ankle ROM may be causing changes in kinematics in the sagittal and frontal planes at the knee joint. Findings from this study may differ from other research to date because of the novel nature of the task performed. Further research is needed to better understand how restrictions in available ankle range of motion can lead to over use injury at the knee.

APPENDIX A: TABLES

Table 1. Subject Demographics (n=30)

	Mean	***±SD***
Height (cm)	173.5	12.1
Weight (kg)	72.0	16.4
Soleus-Limited DF ROM	10.9	4.9
Gastroc-Limited DF ROM	1.7	4.5

Table 2. Joint start values within subjects comparing wedge/no wedge conditions.

Variables	*No Wedge*	*Wedge*	*P*	*Effect Size*	*Observed Power*
Knee Valgus	-1.9±2.7(-2.9, -0.8)	-2.1±2.6(-3.1, -1.1)	0.10	0.07	0.38
Knee Flexion	-4.4±8.1(-7.6, -1.3)	-4.5±7.5(-7.4, -1.6)	0.98	0.01	0.05
Ankle Dorsiflexion	0.7±2.7(-0.3, 1.8)	-8.9±2.8(-10.0, -7.8)	<0.001*	3.4	1.0
Hip Flexion	-8.0±5.9(-10.3, -5.8)	8.6±5.8(-10.8, -6.3)	0.18	2.8	0.27

Note: Values represent mean standard deviation (95% confidence interval). Effect size was calculated by dividing the sums of the means by the larger SD.
* Significantly different between conditions.

Table 3. Peak Kinematic Values during squat descent within subjects comparing wedge/no wedge conditions.

Variables	*No Wedge*	*Wedge*	*P*	*Effect Size*	*Observed Power*
Knee Valgus	-3.7±3.2 (-4.9, -2.4)	-4.3±3.3 (-5.6, -3.0)	0.02*	0.18	0.70
Knee Flexion	96.9±16.9 (90.4, 103.5)	80.6±19.3 (73.1, 88.0)	<0.001 *	0.85	1.0
Ankle Dorsiflexion	-27.3±6.4(-29.8, -24.9)	-28.9 ± 6.6 (-31.5, -26.4)	0.01*	0.24	0.75
Hip Flexion	63.0±13.0(59.0, 68.1)	62.9±14.1(57.4, 68.4)	0.78	0.03	0.06

Note: Values represent mean standard deviation (95% confidence interval). Effect size was calculated by dividing the sums of the means by the larger SD.
* Significantly different between conditions.

Table 4. Joint ROM values within subjects comparing wedge/no wedge conditions.

Variables	*No Wedge*	*Wedge*	*P*	*Effect Size*	*Observed Power*
Knee Valgus ROM	-1.8±2.7(-2.9, -0.8)	-2.2±2.9(-3.3, -1.1)	0.16	0.14	0.28
Knee Flexion ROM	101.4±17.5(94.6, 108.1)	85.0±19.5(77.4, 92.6)	<0.001*	0.84	1.0
Ankle Dorsiflexion ROM	-28.1±6.1(-30.4, -25.7)	-20.0±6.1(-22.4, -17.6)	<0.001*	1.3	1.0
Hip Flexion ROM	71.1±13.8(65.7, 76.7)	71.4±14.7(65.7, 77.1)	0.52	0.02	0.1

Note: Values represent mean standard deviation (95% confidence interval). Effect size was calculated by dividing the sums of the means by the larger SD.
* Significantly different between conditions.

Table 5. Average EMG activity over descent phase in the wedge and no wedge conditions.

Variables	*No Wedge*	*Wedge*	*P*	*Effect Size*	*Observed Power*
Vastus Lateralis	0.62 ± 0.22 (0.54, 0.71)	0.55 ± 0.19 (0.48, 0.62)	0.002*	0.32	0.92
VMO	0.66 ± 0.26 (0.56, 0.76)	0.61 ± 0.21 (0.53, 0.69)	0.025*	0.19	0.63
Soleus	0.24 ± 0.19 (0.17, 0.32)	0.26 ± 0.18 (0.19, 0.33)	0.049*	0.11	0.51
Gastrocnemius	0.19 ± .013 (0.14, 0.23)	0.19 ± 0.14 (0.15, 0.25)	0.98	0	0.24

Note: Values represent mean standard deviation (95% confidence interval). Effect size was calculated by dividing the sums of the means by the larger SD.
. * Significantly different between conditions.

Table 6. Correlations of clinically measured dorsiflexion with kinematic and EMG data.

	Gastroc-Limited Dorsiflexion		Soleus-Limited Dorsiflexion	
	Pearson *r*	*P*	Pearson *r*	*P*
Peak Knee Flexion	0.18	0.36	0.20	0.31
Peak Knee Valgus	-0.07	0.73	0.45	0.82
Peak Ankle Dorsiflexion	-0.11	0.58	-0.17	0.38
Peak Hip Flexion	-0.02	0.93	-0.21	0.30
Vastus Lateralis Mean EMG	-0.15	0.44	-0.12	0.54
Vastus Medialis Oblique Mean EMG	-0.11	0.58	0.06	0.76
Soleus Mean EMG	0.16	0.41	0.09	0.64
Gastrocnemius Mean EMG	0.05	0.81	0.06	0.78

* Significantly different between conditions (P<0.05).

APPENDIX B: FIGURES

Figure 1. Start position for the no-wedge condition.

Figure 2. End position for the no-wedge condition.

Figure 3. Start position for the wedge condition.

Figure 4. End position for wedge condition.

APPENDIX C: MANUSCRIPT

ABSTRACT

The Relationship Between Dorsiflexion Range of Motion and Lower Extremity Movement Patterns and Muscle Activation

Context: Patellofemoral pain syndrome is one of the most common lower extremity injuries afflicting active people, however, the pathology is still not well understood. Many variables have been examined in this area, but distal factors still need to be inspected. Limitations in flexibility at the ankle have been observed in subjects with patellofemoral pain syndrome, but the link between ankle and knee motion has yet to be determined in healthy individuals. **Objective:** To determine the effect of induced gastrocnemius/soleus tightness on lower extremity kinematics and muscle activity. **Design:** Cross-sectional. **Setting:** Research laboratory. **Patients or Other Participants**: Healthy recreationally active subjects (n = 30, height = 173.5 ± 12.1 cm, mass = 72.0 ± 16.4 kg). **Data Collection and Analysis**: Clinically measured dorsiflexion values, start, peak and ROM kinematic variables for knee flexion, ankle dorsiflexion, knee valgus and hip flexion over the descent phase and mean EMG amplitude of the vastus lateralis, vastus medialis oblique, gastrocnemius, and soleus were assessed during a double-leg overhead squat. 2-way repeated measures ANOVAs were run for each dependent variable, and simple correlations were run for the clinically measured dorsiflexion with each of the kinematic and EMG variables. **Results:** During the wedge condition, there was a significant increase in peak knee valgus, decrease in ankle dorsiflexion and knee flexion angle, but no change in hip sagittal plane motion. Vastus lateralis and vastus medialis oblique activity significantly decreased with the wedge condition, while soleus activity increased. There was no change in gastrocnemius activity. **Conclusion:** Limiting ankle dorsiflexion results in changes in kinematics at the knee and subsequent changes in muscle activation. This limitation in ankle sagittal plane motion should be researched further in a patient population. **Key Words:** Knee, Patellofemoral Pain Syndrome, Ankle Dorsiflexion, Soleus.

INTRODUCTION

Injuries in physically active populations most often occur in the lower extremity, with up to 42 percent of these injuries occurring at the knee (Hreljac 2003). Chronic knee pain, such as patellofemoral pain syndrome (PFPS) is one of the most common forms of knee overuse injury (DeHaven and Lintner 1986; Duffey, Martin et al. 2000; Taunton, Ryan et al. 2002; Hreljac 2003). PFPS is a term describing achy, diffuse pain surrounding the patella's articulation with the femur and presents itself in a variety of individuals from highly competitive athletes, to those involved in recreational activities. Symptoms of PFPS are usually exacerbated with activities which load the knee such as stair climbing, squatting, and sitting for extended periods of time (Loudon, Wiesner et al. 2002; Earl, Hertel et al. 2005). These symptoms include anterior knee pain, crepitus, and joint stiffness leading to a decrease in physical activity and difficulty performing activities of daily living. Anterior cruciate ligament (ACL) injury is one of the most common acute, catastrophic injuries at the knee, especially in athletic populations(Agel, Arendt et al. 2005). ACL injury and PFPS are commonly associated with similar risk factors (Powers 2003; Crossley, Cowan et al. 2004; Garrett and Yu 2007). Due to the consequences associated with PFPS and ACL injury, it is important to understand potential mechanisms predisposing an individual to PFPS or ACL injury to successfully prevent and rehabilitate these injuries.

Previous research on PFPS and ACL injury has examined a variety of lower extremity biomechanical variables to identify risk factors. Specifically, increased quadriceps angle (Q angle), has been linked to knee valgus position during dynamic activities and increased risk for PFPS and ACL injury (Moss, Devita et al. 1992; Powers 2003; Green 2005; Hewett, Ford et al. 2006; Piva, Fitzgerald et al. 2006). Several studies indicate that individuals suffering from PFPS demonstrate increased Q angle; however, this research has not been shown to be a risk factor for the development of PFPS (Boucher, King et al. 1992; Moss, Devita et al. 1992; Tang, Chen et al. 2001; Earl, Hertel et al. 2005). Increased Q angle and knee valgus positioning during activity are believed to facilitate PFPS by causing patellofemoral joint (PFJ) malalignment and periarticular irritation due to an increased lateral force on the patella via the association of the quadriceps musculature and iliotibial band with the lateral retinaculum (Moss, Devita et al. 1992; Green 2005). Increased Q angle is also generally associated with an increased risk for ACL injury (Powers 2003; Hewett, Ford et al. 2006). Altered activation of the vastus medialis oblique has also been theorized to contribute to PFPS (Cowan, Bennell et al. 2002; Mohr, Kvitne et al. 2003). Researchers theorize that decreased or delayed activation of the VMO in comparison to the vastus lateralis may lead to lateral patella tracking, which may facilitate the development of PFPS due to altered compressive forces at the PFJ (Souza and Gross 1991; Powers, Landel et al. 1996; Miller, Sedory et al. 1997; Cowan, Bennell et al. 2001).

Increased knee flexion angles are thought to increase compressive forces at the PFJ, possibly leading to PFPS in individuals who are involved in activities that use greater knee flexion angles. However, in samples with PFPS, decreased knee flexion has been observed during functional tasks, and is theorized to be a compensation as the quadriceps do not allow the flexion angles with highest PFJ pressures (Salsich, Brechter et al. 2001; Earl, Hertel et al. 2005). Decreased knee flexion angle during high-demand tasks has also been theorized to be a risk factor for ACL injury due to the relationship between decreased knee flexion and an increase in anterior tibial shear force (Garrett and Yu 2007; Sell, Ferris et al. 2007). Anterior tibial shear force is the primary force that loads the ACL, so having decreased knee flexion during high-demand tasks could put an individual at higher risk for injuring their ACL. While there are several lower extremity biomechanical variables that have been shown to differ between PFPS and healthy individuals it is not clear why differences in these biomechanical variables would develop.

Limited ankle dorsiflexion range of motion due to tightness of the gastrocnemius (Witvrouw, Lysens et al. 2000) and soleus (Piva, Goodnite et al. 2005) have also been reported in samples of individuals with PFPS. Piva et al. (2005) demonstrated that individuals with PFPS had significantly less flexibility of the gastrocnemius and soleus muscles in comparison to healthy controls. Similarly, Witvrouw et al. (2000) revealed decreased gastrocnemius flexibility in PFPS subjects compared to controls. Piva et al. (2005) describe a series of biomechanical compensations in those individuals with limited ankle dorsiflexion which may increase the risk for developing PFPS. Specifically, decreased ankle dorsiflexion during weight bearing tasks requiring an individual to lower their body's center of mass may cause increased subtalar joint pronation and tibial internal rotation to gain additional motion. Excessive tibial internal rotation is then theorized to increase femoral internal rotation and Q-angle / knee valgus position and ultimately result in greater patellofemoral contact pressure.

Limited ankle dorsiflexion ROM due to limited gastrocnemius and/or soleus muscle flexibility may also facilitate a change in knee flexion and quadriceps muscle activation. Greater knee flexion angles have been reported to occur when ankle dorsiflexion range of motion is limited, allowing the individual to successfully lower their body's center of mass (DiStefano LJ 2006). Increased knee flexion would require increased quadriceps activation to offset the increased external knee flexion moment and control the body's mass while being lowered (Salsich, Brechter et al. 2001; Earl, Hertel et al. 2005). The combination of increased knee flexion and quadriceps activation has been shown to increase patellofemoral contact pressures (Salsich, Brechter et al. 2001; Earl, Hertel et al. 2005), which may ultimately increase the risk for PFPS. Unfortunately, research has not been performed to determine the influence of limited ankle dorsiflexion on lower extremity kinematics and muscle activation patterns. To better understand the role of gastrocnemius and soleus muscle flexibility as potential risk factors for PFPS it is important to understand the influence of ankle dorsiflexion range of motion during weight bearing tasks on lower extremity kinematics and muscle activation variables that are believed to be risk factors for PFPS. Therefore the primary purpose of this study was to determine the effect of reduced dorsiflexion ROM on knee flexion angle, knee valgus angle, ankle dorsiflexion angle, hip flexion angle, quadriceps activation, gastrocnemius activation, and soleus activation during the descent phase of a squat task. The secondary purpose of this study was to investigate the relationships between gastrocnemius and soleus flexibility measures with these same dependent variables.

METHODS

Subjects

Subjects who participated in this study were healthy, asymptomatic, and ranging in age from 18 to 30 years old. Thirty subjects completed the test protocol (15 m, 15 f, height = 173.5 ± 12.1cm, weight = 72.0 ± 16.4kg). Mean soleus-limited dorsiflexion was 10.9 degrees ± 4.9 degrees. Mean gastrocnemius-limited dorsiflexion was 1.7 degrees ± 4.5 degrees. All subject demographic information can be found in Table 1. The subjects were recruited from the general student and faculty/staff populations at the University of North Carolina at

Chapel Hill (UNC-CH) via informational flyers posted across the campus and verbal recruitment by the study principal investigator (EM). For inclusion in the study, subjects were determined to be physically active, which was defined as 30 minutes of physical activity a day for a minimum of 3 days a week. Additionally, subjects must have had current or former participation, at least one year of high school or college varsity, in organized soccer, volleyball, basketball or lacrosse. Subjects were excluded if they reported lower extremity injury in either leg within the past 3 months that caused them to not participate in physical activity for at least one day or required physician referral. Subjects who reported lower extremity surgery within the past year or who had current knee pain at time of testing session were also excluded from this study. Prior to study participation all subjects completed a questionnaire regarding their inclusion / exclusion criteria status and signed an informed consent form approved by the Institutional Review Board.

Instrumentation

A universal 12-inch goniometer was used to measure passive ankle dorsiflexion range of motion (ROM) at 0° and 90° of knee flexion. Electromyographic (EMG) data were collected using the Delsys Bagnoli-8 Non-telemetered system (Delsys, Inc. Boston MA). Unit specifications included a CMRR of 92 dB and amplifier gain of 1000. EMG data was collected at 1200 Hz. Kinematic data was obtained using 7 Vicon MX-40 Infrared Cameras at a rate of 120 Hz (Vicon Motion Systems, Lake Forest, CA). Calibration volume for the Vicon MX-40 Infrared Cameras was 2.5 m long /x 1.5 m wide x 2.5 m high. All kinematic and EMG data were collected using the Nexus software (version 1.0) (Vicon Motion Systems, Lake Forest, CA).

Testing Procedures

Subjects reported to the Sports Medicine Research Laboratory for a single testing session lasting approximately 1 hour. Subjects read and signed an informed consent for the study prior to performing data collection. The researcher reviewed the inclusion and exclusion criteria, procedures, and any possible positives and/or negatives to their involvement in the study, and the subject was given an opportunity to ask any questions he or she may have had regarding the study prior to the start of data collection. The subjects were required to wear standard running shoes, spandex shorts, and a spandex t-shirt or sports bra. Data from the subject's dominant leg was used for all data analyses and the dominant limb was defined as the leg used to kick a ball for maximal distance.

Prior to subject set-up and data collection the subject warmed up on a stationary cycle ergometer (Schwinn Airdyne Upright Bike, Nautilus, Inc.) for 5 minutes at a self-selected pace. Flexibility of the gastrocnemius and soleus muscles was assessed by measuring the amount of passive ankle dorsiflexion range of motion. Gastrocnemius and soleus flexibility were measured in a counterbalanced order. Gastrocnemius muscle flexibility was measured with the knee positioned in 0° of flexion with the subject in the long sitting position. Soleus muscle flexibility was measured with the knee positioned in 90° of flexion with the subject sitting on the edge of a treatment table. During both gastrocnemius and soleus flexibility measures, the principal investigator passively dorsiflexed the subject's ankle until the point of soft tissue resistance while maintaining the subtalar joint neutral position by palpating the medial and lateral aspect of the talar head. Ankle dorsiflexion angle was measured with a standard goniometer as the angle formed by the shaft of the fibula (line drawn from fibular head to lateral malleolus) and the lateral midline of the foot (line drawn along the border of the rearfoot / calcaneus and base of fifth metatarsal) (Piva, Fitzgerald et al. 2006). This was repeated three times each for gastrocnemius and soleus flexibility measures. The arithmetic mean of each position was recorded and used for data analysis. Intra-rater reliability for soleus ($ICC_{2,k}$= 0.84, SEM= 2.03) and gastrocnemius ($ICC_{2,k}$= 0.86, SEM= 1.68) range of motion was established to be good prior to the beginning of the study.

Following range of motion measurements the subject was prepared for EMG and motion analysis data collection. Each subject's skin was shaved and cleaned with gauze and isopropyl alcohol prior to application of surface electrodes. Surface EMG electrodes were attached over the vastus medialis oblique (VMO), vastus lateralis (VL), soleus (SOL), and lateral gastrocnemius (LG) musculature. The electrodes for the quadriceps were placed over the VL, approximately 10cm superior and 7 cm lateral to the superior border of the patella oriented at 10 degrees to the vertical (Cowan, Bennell et al. 2002). For the VMO the electrode were placed approximately 4 cm superior and 3 cm medial to the superomedial border of the patella oriented at a 55 degree angle(Cowan, Bennell et al. 2002). The electrode for the LG was placed over the bulge of the lateral head of the gastrocnemius (Basmajian, Blumenstein, and Dismatsek, 1980). Electrode placement for the SOL was placed just medial to the medial aspect of the achilles tendon, inferior to the midpoint of the lower leg (Basmajian, Blumenstein, and Dismatsek, 1980). A reference electrode was placed over the tibial tuberosity of the test limb. All electrode placements were reinforced with pre-wrap and athletic tape and were verified and checked for cross-talk with manual muscle testing prior to moving on with data collection.

Before each testing period, the data collection volume for kinetics and kinematics was calibrated. Reflective markers were attached bilaterally to subjects on the following landmarks: L5-S1 space, ASIS, greater trochanter, medial and lateral femoral epicondyles, mid-thigh, mid shank, medial and lateral malleoli, head of the 5th metatarsal, head of the first metatarsal, calcaneus, and acromion process. All markers were placed over clothing or footwear if they could not be applied directly to the skin at a given landmark. Prior to trial data collection data, static trials were performed with the subjects facing in the positive-x axis direction, feet shoulder-width apart, and both arms abducted to 90 degrees. Medial malleolus and medial femoral condyle markers were removed from both legs prior to beginning trial data collection.

Three-dimensional (3-D) videographic and electromyographic data were collected for each subject as they performed a series of double leg squats. A global reference system was defined using a right hand coordinate system, in which the x-axis was positive in the anterior direction, the y-axis was positive to the left of each subject, and the z-axis was positive in the superior direction.

Subjects performed seven double leg squat trials under two separate conditions: a no-wedge condition with the foot positioned flat on the floor, and a wedge condition with a 12° forefoot angle. The wedge ran along the full length of the foot. The forefoot portion of the wedge was 12° relative to the hindfoot and the medial and lateral aspects of the wedge were at a 0° relative to each other. The wedge was designed to place the subject's ankle in 12° of ankle dorsiflexion while in the upright position before performing the double leg squat task, thereby minimizing the amount of dorsiflexion motion during the double leg squat. A 12° wedge was determined through pilot testing to cause a change in kinematics, but not make the task impossible to perform. The order in which the test conditions were performed was counterbalanced.

During the squat task, the subject was instructed to perform a double leg squat "as if they are sitting back in a chair" with their arms overhead while keeping them in line with their ears, and heels on the floor. The subject's feet were positioned shoulder-width apart, with their feet facing forward (toward positive x). The subject was instructed to squat to a depth as far as they were comfortable. The subject was allowed a maximum of five practice repetitions and was provided two minutes of rest between the practice and test trials. Subjects performed seven test repetitions per trial period with one minute rest between the sets. The two sets consisted of one set of the no wedge and one set of the wedge condition. The middle five trials were used for data reduction and statistical analysis. EMG measurements were analyzed in the descending phase for mean amplitude of activity during the overhead squat. Kinematic data collected included peak knee flexion angle, peak ankle dorsiflexion angle, peak hip flexion angle, and peak knee valgus angle.

After all repetitions of the test trials were performed, maximal voluntary isometric contractions (MVICs) were performed for normalization of the EMG data. Subjects performed 3 trials for each MVIC. The mean of the middle 3 seconds of each trial were used to find the total arithmetic mean for normalization of the EMG data. MVIC's were performed for the VMO, VL, LG, and SOL musculature. For VMO and VL MVIC's, the subject was seated in a dynamometer chair with knees and hips flexed to 90 degrees and was instructed to "kick out" against the resistance of the strap to extend the knee and for five seconds. Soleus and gastrocnemius MVICs were collected using a nylon strap across the metatarsal heads (ball of foot) of the test side. Soleus MVIC was collected with the subject in a quadriped position with knees and hips flexed to 90 degrees on the table with a strap around the heads of the metatarsals of the test limb. Gastrocnemius MVICs were collected with the subject lying prone with the test limb off the end of the table and the strap across the metatarsal heads. For both the soleus and gastrocnemius MVICs, the subjects plantar flexed against the strap with maximal effort.

Data Processing and Reduction

EMG mean amplitude of the quadriceps, gastrocnemius and soleus were normalized to the maximum voluntary isometric contraction for each subject. Mean amplitude measures were calculated for quadriceps, gastrocnemius and soleus for the descending phase. Descending phase was defined as the onset of motion through peak knee flexion angle (Figures 1-4). Peak knee flexion was defined as greatest knee flexion angle reached by the subject during the task. Peak knee valgus angle was defined as the peak frontal plane motion of the knee toward the midline. Peak ankle dorsiflexion angle was defined as the greatest point of dorsiflexion angle through each phase of the task. All data were imported into Motion Monitor Software (version 7.72) (Innovative Sports Training, Inc. Chicago IL). A custom MatLab program was used to determine kinematic variables during the squatting task (Mathworks, Natick MA). EMG data were filtered with a bandpass filter between 10 and 350 Hz using 4^{th} order Butterworth filter. EMG data were further smoothed by taking the root mean square over a 20 ms time constant. Kinematic data were also filtered at 12 Hz using a 4^{th} order Butterworth filter with a 12 Hz cut off frequency.

Statistical Analyses

All data analyses were performed using SPSS version 13.0 (SPSS, Inc. Chicago, IL). Pearson product moment correlations were performed to determine the relationship between gastrocnemius and soleus flexibility measures and each of the following dependent variables: peak angles during the descent phase of ankle dorsiflexion, knee valgus, knee flexion and hip flexion, as well as mean soleus activity, quadriceps activity, and gastrocnemius activity. Separate repeated measures ANOVAs were run for each: mean EMG amplitude for quadriceps, gastrocnemius, and soleus, and start angles, peak angles, and ROM values for ankle dorsiflexion, knee valgus, knee flexion, and hip flexion during the descent phase of the squat. The within subject factor was wedge condition (2 levels: wedge, no wedge). A priori alpha level was set at 0.05.

RESULTS

Thirty subjects completed the test protocol (15 males and 15 females). Mean height was 173.5 cm ± 12.1 cm. Mean weight was 72.0 kg ± 16.4 kg. Mean soleus-limited dorsiflexion was 10.9 degrees ± 4.9 degrees. Mean gastrocnemius-limited dorsiflexion was 1.7 degrees ± 4.5 degrees. All subject demographic information can be found in Table 1.

We observed a significant decrease in peak knee flexion angle when the overhead squat was performed on the wedge ($F_{(1, 27)}$=105.5, $p \leq 0.001$) (Table 3). We also observed a significant decrease in knee flexion range of motion during the wedge condition ($F_{(1, 27)}$=90.6, $p \leq 0.001$) (Table 4). This decrease in knee flexion during the wedge condition was coupled with a significant increase in peak knee valgus angle ($F_{(1, 27)}$=6.6, p=0.02) (Table 3). Knee valgus ROM also significantly increased during the wedge condition ($F_{(1, 27)}$=2.1, p=0.02) (Table 4).

We observed significant changes in motion at the ankle as well. The ankle dorsiflexion start angle was significantly increased with the wedge condition ($F_{(1, 27)}$=3.0, $p \leq .001$) (Table 2). Participants also went through significantly less ankle ROM with the wedge in place ($F_{(1, 27)}$=158.3, $p \leq .001$) (Table 4). There was a significant difference in peak ankle dorsiflexion as participants reached a greater amount of dorsiflexion with the wedge in place ($F_{(1, 27)}$=7.4, p=0.01) (Table 3). Clinically measured dorsiflexion ROM (knee extended and knee flexed) did not correlate with any dependent variable (Table 6).

We observed significant changes in the soleus and quadriceps muscle activation. Soleus activity increased during the descent phase when the squat was performed on the wedge ($F_{(1, 27)}$=4.2, p=.049). However, when we examined quadriceps activity both the VL and the VMO significantly decreased with the wedge condition during the descending phase (VL: $F_{(1, 27)}$=12.2, p=0.002; VMO: $F_{(1, 27)}$=5.6, p=0.03) of the squat. We observed no differences in gastrocnemius EMG amplitude for the two squat conditions for the descending ($F_{(1, 27)}$=1.7, p=0.21) phase (Table 4).

DISCUSSION

The finding of key importance in this study was that knee valgus increased when the overhead squat task was performed on the wedge. We hypothesized this would occur because the wedge would lead to compensations at the knee and/or hip due to the decreases in available ankle range of motion. Our results support this hypothesis and provide further support that restrictions in ankle motion (in this case with the wedge in place) alters kinematics up the kinetic chain.

Participants in this investigation increased their knee valgus angle by approximately one degree when sagittal plane ankle range of motion was limited with the wedge. While the increase in knee valgus angle during the wedge condition was small in absolute magnitude (1° increase) this represented an overall increase in knee valgus angle of 16% during the wedge condition compared to the no wedge condition. Given the smaller available range of knee valgus motion in comparison to knee flexion we feel that this statistically significant increase in knee valgus angle is clinically important. Previous research has reported that similar increases in knee valgus angle (1-2º increase) can lead to an increased risk of injury (Joseph, Tiberio et al. 2008). Other research has shown that placing a wedge under the heel to increase the starting plantar flexion angle and allow for greater ankle dorsiflexion motion during a squat caused a decrease in medial knee displacement as compared to performing a squat without the wedge (Bell, In Press). The findings from this investigation along with our study highlight the influence of ankle dorsiflexion range of motion on knee valgus motion during tasks that involve a squatting motion.

We also demonstrated that limiting the amount of available ankle dorsiflexion range of motion during the wedge condition resulted in a concomitant decrease in peak knee flexion angle and range of motion. Peak knee flexion angle decreased by approximately 17º during the wedge condition compared to the no wedge condition. Interestingly, this large change in knee flexion angle represented a 16% decrease in knee flexion, which is identical to the percent increase in knee valgus angle. We hypothesize that limited ankle dorsiflexion range of motion during the wedge condition resulted in an inability to achieve full knee flexion (16% decrease) which resulted in a compensatory increase in knee valgus angle (16% increase) as the individual attempted to lower their body's center of mass during the squat motion. We did not observe any changes in hip flexion motion during the wedge condition, which suggests that squat kinematic alterations during the wedge condition are most readily apparent at the knee (decreased knee flexion and increased knee valgus).

Ankle dorsiflexion range of motion significantly decreased by 8º during the wedge condition, which represents a 27% decrease in motion compared to the no wedge condition. This indicates that the wedge did, in fact, limit dorsiflexion as we hypothesized it would, and the compensations seen at the knee are likely due to limited ankle dorsiflexion motion. We hypothesize that the restrictions created in ankle dorsiflexion motion during the wedge condition caused the obligatory compensations of decreased knee flexion angle and increased knee valgus angle.

The compensatory changes associated with limiting ankle dorsiflexion motion may have considerable clinical relevance as decreased knee flexion and increased knee valgus have been implicated as body postures associated with increased risk of PFPS and ACL injury (Messier, Davis et al. 1991; Moss, Devita et al. 1992; Malinzak, Colby et al. 2001; Crossley, Cowan et al. 2004; Hewett, Ford et al. 2006). Increased knee valgus has been implicated as a risk factor in PFPS due to the forces which subsequently occur at the PFJ. Pathologic samples have shown knee valgus positions just two degrees greater than those of symptom free samples (Moss, Devita, 1992). This increase in knee valgus is often associated with tightness of the IT band and a lateral tracking of the patella in the PFJ (Earl, Hertel et al. 2005; Green 2005; Piva, Fitzgerald et al. 2006). This malalignment of the patella can cause an increase in contact pressure over a smaller area of the lateral surface of the femoral trochlea and an increase in tensile force on the medial stabilizing structures (Pangiotopoulos, et al 2005). This alteration in contact stresses are theorized to lead to the development of PFPS (Powers 2003). Increased knee valgus has been implicated as a risk factor for ACL injury in the literature through its association with increased Q angle (Powers 2003; Hewett, Ford et al. 2006).

Decreased knee flexion angle has also been implicated in injuries at the knee. Flexibility measures of the quadriceps have been shown to be decreased in subjects suffering PFPS, possibly as compensation for other kinematic variations or for avoidance of pain (Piva, Fitzgerald et al. 2006). Additionally, decreased knee flexion angle during dynamic tasks in individuals with PFPS has been reported by several researchers (Salsich, Brechter et al. 2001; Crossley, Cowan et al. 2004). Decreased knee flexion during higher-demand tasks has also been connected with increased risk of anterior crutiate ligament (ACL) injury because of its association with increased anterior tibial shear force. Anterior tibial shear force is the primary force which loads the ACL, so having a decreased knee flexion angle during dynamic activities such as jumping, running and cutting may predispose an individual to an ACL injury(Garrett and Yu 2007; Sell, Ferris et al. 2007). Furthermore, recent research has purported that females are at higher risk for ACL injury (Agel, Arendt et al. 2005; Mihata, Beutler et al. 2006) because females tend to have decreased knee flexion angles during high demand functional tasks such as cutting or jump-landing maneuvers when compared to their male counterparts (Malinzak, Colby et al. 2001; Chappell, Creighton et al. 2007). We hypothesize that these changes in kinematics seen with limited ankle dorsiflexion may load the PFJ and ACL similarly and potentially result in increased risk of injury to these structures. We did not examine joint loading in this study, but this should be examined in future research.

Previous research also supports the concept that decreased ankle dorsiflexion motion may be a risk factor for lower extremity injury. Gastrocnemius and soleus flexibility deficits have been reported in samples of individuals with PFPS (Piva, Fitzgerald et al. 2006, Green 2005). We speculate that decreased knee flexion and increased knee valgus seen were a function of the limited available dorsiflexion in our study, which may imply that the gastrocnemius and soleus flexibility deficits seen in pathologic samples may be a precursor, and not compensation to PFPS. The compensations seen in this study are commonly speculated to be related to PFPS and ACL injury, which may indicate that decreased range of motion at the ankle may also play a role in making individuals more susceptible to overuse or acute injury at the knee.

Limiting ankle dorsiflexion during the squatting task resulted in decreased activity of the quadriceps musculature and increased activity of the soleus during the descent phase of the squat. These changes are likely due to the changes observed in knee flexion and ankle dorsiflexion kinematics during the wedge condition. As previously indicated there was a significant decrease in peak knee flexion angle and range of motion during the wedge condition, which most likely accounts for the decrease in quadriceps (VMO and VL) muscle activity. Quadriceps activation is necessary during the descent phase of the squat to control knee flexion motion and prevent the knee from collapsing in the sagittal plane. By restricting the amount of knee flexion motion during the wedge condition less quadriceps activity was required. Soleus muscle activation was significantly increased during the descent phase of the squat task even though there was a significant decrease in ankle dorsiflexion range of motion during the wedge condition. While ankle dorsiflexion range of motion was decreased the peak ankle dorsiflexion angle was slightly increased during the wedge condition. Thus, we believe that greater soleus activation was required during the wedge condition to control the larger ankle dorsiflexion angle as the soleus acts to eccentrically resist ankle dorsiflexion motion. Gastrocnemius activity remained unchanged, possibly due to its diarthodial nature. During the squatting task, at both ends of the motion, one joint attempts to shorten the gastrocnemius while the other lengthens it, causing it to play no significant role in the control of the knee or ankle motion.

This study had several limitations. Squat depth and cadence were not controlled because we wanted to observe “natural” movement pattern compensations imposed by the wedge. Future research should consider controlling for these variables to see how they may differ from the outcomes observed in this study. A second limitation of the study is the wedge itself. There might be changes caused by the wedge that we did not consider and these changes may explain results such as alterations to center of mass. However, given that this is the first study concerning this combination of variables, we felt this was an appropriate intervention. Additionally, performing a squat on a wedge is not a realistic situation. Future research in this area should use an intervention which enables the foot to remain in a locked but functioning position, using a brace technique or other device limiting sagittal motion at the ankle. The position of the wedge in the test area was also not controlled by the principal investigator. There was a significant difference in distance between the feet comparing wedge to no wedge conditions (0.10 m and 0.12 m, respectively). Future research should control for distance between the feet to ensure any changes seen were not due to differences in subject positioning.

Clinically, these findings may suggest that the natural compensation to gastrocnemius and soleus tightness is decreased sagittal plane motion and increased frontal plane motion at other joints up the kinetic chain. Over time this may lead to other imbalances throughout the kinetic chain, making the individual more susceptible to overuse or acute knee injuries such as PFPS or ACL injury. Most research has assessed static alignment issues at the foot, and hip muscle imbalances in relation to PFPS, but few have considered the ankle joint. This study suggests that, for at least a portion of individuals, restrictions in available ankle ROM may be causing changes in kinematics in the sagittal and frontal planes at the knee joint. Findings from this study may differ from other research to date because of the novel nature of the task performed. Further research is needed to better understand how restrictions in available ankle range of motion can lead to over use injury at the knee.

APPENDIX D: 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: Assessment of lower extremity EMG and kinematics during functional tasks in healthy males and females.

Principal Investigator: Elisabeth C. Macrum, LAT, ATC, CSCS
UNC-Chapel Hill Department: Exercise and Sport Science
UNC-Chapel Hill Phone number: 207-432-2871
Email Address: emacrum@email.unc.edu
Co-Investigators: Meghan C. Walsh (mcwalsh@email.unc.edu), J. Troy Blackburn, Michelle Boling (boling@email.unc.edu), Melanie McGrath (mmcgrath20@hotmail.com), David Bell (bell@email.unc.edu), Benjamin Goerger
Faculty Advisor: Darin Padua, PhD, ATC
Funding Source:

Study Contact telephone number: 207-432-2871
Study Contact email: emacrum@email.unc.edu

<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 research study is to learn about joint movement and muscle activity during two tasks that are similar to movements found in sport activities. Learning about these factors may aid in the development of injury prevention and treatment programs.

You are being asked to be in the study because you are a healthy, recreationally active person who has participated in sports that involve movements similar to the tasks being tested.

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

You should not be in this study if you are not between the ages of 18-30. You should also not be in this study if you have sustained a lower extremity injury within the past six months in either leg. Lower extremity injury is defined as any injury sustained resulting in more than one day lost in physical activity or referral to a physician. Subjects will also be excluded if they have a history of surgery to the lower extremity or history of ACL surgery in the past 2 years. You should also not be in this study if you are or may be pregnant.

How many people will take part in this study?

If you decide to be in this study, you will be one of approximately 30 people in this research study.

How long will your part in this study last?

Participation in this study will last for a single testing session, lasting approximately one hour.

What will happen if you take part in the study?

The data session consists of performance of two tasks, one jump landing task and one squat task. You are asked to wear clothing (t shirt and shorts) and running shoes appropriate for participating in physical activity. When you arrive at the laboratory, you will be asked to fill out a short questionnaire and your height and weight will be measured by the primary investigator. Band-aid like electrodes and sensors that will monitor muscle activity and joint motion will be attached over muscles in the buttocks, thigh and lower leg, and on your dominant leg (the leg used to kick a ball for maximum distance). You will then be allowed to practice the tasks. For the jump landing task, you will be jumping from a platform 30 cm off the ground onto a stable surface. When you land, you will then be instructed to jump straight up for maximum vertical distance. For squat task you will be asked to perform a motion like you are sitting back into a chair while your arms are up by your ears. Once you feel comfortable with the tasks you will be asked to perform a series of ten jumps and two sets of five squats. During one set of the squat tasks you will be asked to place both of your feet on a slanted board while squatting. In order to be eligible for participation in the study, you must complete all portions listed here.

What are the possible benefits from being in this study?

Research is designed to benefit society by gaining new knowledge. You may not benefit personally from participating in this study. However, you will learn techniques for jumping and squatting that may help prevent you from sustaining a lower extremity injury in the future.

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

As with any physical activity, participation in this study carries a risk of bodily injury. The motions that you will be asked to perform are ones that repeatedly occur during physical activity. Therefore, you should be familiar and able to perform the tasks with minimal injury risk. To further minimize injury risk, you will be allowed to warm up and stretch to prepare for testing. In case of injury, medical personnel (certified athletic trainers) will be located in the same building as the testing session. During the electrode and sensor placement, you will be properly draped with a towel to ensure privacy and minimize risk of embarrassment, and the electrodes will be applied by an investigator of the same sex. It is also possible that the application of the electrodes may cause minor skin irritation. You are free to cease participation at any time.

In addition, there may be uncommon or previously unknown risks that might occur. You should report any problems to the researchers.

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.

All paper documentation will be identified with a subject number as well. They will be kept in a secured location for the duration of the study and destroyed once they are no longer needed for research purposes.

Any data stored on a computer will be identified by a subject number and protected by a password which only the primary investigator and anyone else directly involved in data collection and reduction for this study will have access to.

A copy of this consent form will go in to your medical record. This will allow the doctors caring for you to know what study medications or tests you may be receiving as a part of the study and know how to take care of you if you have other health problems or needs during the study.

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 anything for taking part in this study.

Will it cost you anything to be in this study?

It will not cost you anything in addition to what you will be billed for your routine medical care to be in this study. All tests, visits or procedures other than what is done for this study will be related to medical care that is part of the usual care for your condition and would be suggested even if you decided not to be in the research study. Here are some examples of standard medical care of you that may be performed within this study:

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.

Who is sponsoring this study?

There is no sponsorship for this study.

What if you have questions about this study?

You have the right to ask, and have answered, any questions you may have about this research. If you have questions, 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 E: QUESTIONNAIRE

University of North Carolina – Chapel Hill
Research Study Questionnaire
Adult Subjects

Medical IRB Study #

Title of Study: The Relationship Between Anterior Tibial Shear Force and Quadriceps\Hamstring Strength, Knee Flexion Angle, Hip Flexion Angle, and Trunk Flexion Angle during a Jump Landing Task
Principal Investigator: Douglas R. Bennett, LAT, ATC
UNC-CH Department: EXSS
Phone Number: 919-962-7187
Co-Investigators: Darin Padua, PhD, ATC; Troy Blackburn, PhD, ATC; Michelle Boling, MS, ATC; Melanie McGrath, MS, ATC; Chris Hirth MS, PT, ATC
Sponsor: None

Name__________________________ Age___________________________

Height (cm) _____________________ Weight (kg)_____________________

1. Are you currently in good general health?

YES / NO

2. Do you currently have a lower extremity injury that has required days missed from physical activity?

YES / NO

3. Do you have a prior history of ACL injury, ligamentous reconstruction, or any knee surgery within the past two years?

YES / NO

4. Do you have any current symptoms of injury?

YES / NO

5. How often do you exercise per week? __________________ Days

6. Approximately how many minutes do you exercise per day?____________Minutes

7. What type of exercise activity do you most often participate in (soccer, volleyball, basketball, etc.)?

____

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." Am J Sports Med **33**(4): 524-30.

Baggett, B. D. and G. Young (1993). "Ankle joint dorsiflexion. Establishment of a normal range." J Am Podiatr Med Assoc **83**(5): 251-4.

Basmajian, J. V. (1980). "Electromyography--dynamic gross anatomy: a review." Am J Anat **159**(3): 245-60.

Boucher, J. P., M. A. King, et al. (1992). "Quadriceps femoris muscle activity in patellofemoral pain syndrome." Am J Sports Med **20**(5): 527-32.

Chappell, J. D., R. A. Creighton, et al. (2007). "Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury." Am J Sports Med **35**(2): 235-41.

Cowan, S. M., K. L. Bennell, et al. (2002). "Physical therapy alters recruitment of the vasti in patellofemoral pain syndrome." Med Sci Sports Exerc **34**(12): 1879-85.

Cowan, S. M., K. L. Bennell, et al. (2001). "Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain syndrome." Arch Phys Med Rehabil **82**(2): 183-9.

Crossley, K. M., S. M. Cowan, et al. (2004). "Knee flexion during stair ambulation is altered in individuals with patellofemoral pain." J Orthop Res **22**(2): 267-74.

DeHaven, K. E. and D. M. Lintner (1986). "Athletic injuries: comparison by age, sport, and gender." Am J Sports Med **14**(3): 218-24.

DiStefano LJ, P. D., Guskiewicz KM, Hirth CJ, Brown CN, Herman DC (2006). Ankle Bracing Affects Lower Extremity Kinematics, But Does Not Affect Vertical Ground Reaction Forces During A Jump-Landing. National Athletic Trainer's Association Annual Conference, Atlanta, Georgia, Journal of Athletic Trainer.

Duffey, M. J., D. F. Martin, et al. (2000). "Etiologic factors associated with anterior knee pain in distance runners." Med Sci Sports Exerc **32**(11): 1825-32.

Earl, J. E., J. Hertel, et al. (2005). "Patterns of Dynamic Malalignment, Muscle Activation, Joint Motion, and Patellofemoral-Pain Syndrome." JOURNAL OF SPORT REHABILITATION **14**(3): 215.

Fulkerson, J. P. and E. A. Arendt (2000). "Anterior knee pain in females." Clin Orthop Relat Res(372): 69-73.

Garrett, W. E. and B. Yu (2007). "Anterior cruciate ligament injury mechanisms and risk factors." J Orthop Sports Phys Ther **37**(2): A10-1.

Green, S. T. (2005). "Patellofemoral syndrome." Journal of Bodywork and Movement Therapies **9**: 16-26.

Grelsamer, R. P. and J. R. Klein (1998). "The biomechanics of the patellofemoral joint." J Orthop Sports Phys Ther **28**(5): 286-98.

Gross, M. T. and J. L. Foxworth (2003). "The role of foot orthoses as an intervention for patellofemoral pain." J Orthop Sports Phys Ther **33**(11): 661-70.

Hewett, T. E., K. R. Ford, et al. (2006). "Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention." Am J Sports Med **34**(3): 490-8.

Hodgson, J. A. (1983). "The relationship between soleus and gastrocnemius muscle activity in conscious cats--a model for motor unit recruitment?" J Physiol **337**: 553-62.

Holmes, S. W., Jr. and W. G. Clancy, Jr. (1998). "Clinical classification of patellofemoral pain and dysfunction." J Orthop Sports Phys Ther **28**(5): 299-306.

Hreljac, A. (2003). "Etiology, prevention, and early intervention of overuse injuries in runners: a biomechanical perspective." Phys Med Rehabil Clin N Am **2005**: 651-67.

Joseph, M., D. Tiberio, et al. (2008). "Knee valgus during drop jumps in National Collegiate Athletic Association Division I female athletes: the effect of a medial post." Am J Sports Med **36**(2): 285-9.

Kavounoudias, A., R. Roll, et al. (2001). "Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation." J Physiol **532**(Pt 3): 869-78.

Levinger, P. and W. Gilleard (2007). "Tibia and rearfoot motion and ground reaction forces in subjects with patellofemoral pain syndrome during walking." Gait Posture **25**(1): 2-8.

Loudon, J. K., D. Wiesner, et al. (2002). "Intrarater Reliability of Functional Performance Tests for Subjects With Patellofemoral Pain Syndrome." J Athl Train **37**(3): 256-261.

Lun, V., W. H. Meeuwisse, et al. (2004). "Relation between running injury and static lower limb alignment in recreational runners." Br J Sports Med **38**(5): 576-80.

Malinzak, R. A., S. M. Colby, et al. (2001). "A comparison of knee joint motion patterns between men and women in selected athletic tasks." Clin Biomech (Bristol, Avon) **16**(5): 438-45.

Messier, S. P., S. E. Davis, et al. (1991). "Etiologic factors associated with patellofemoral pain in runners." Med Sci Sports Exerc **23**(9): 1008-15.

Mihata, L. C., A. I. Beutler, et al. (2006). "Comparing the incidence of anterior cruciate ligament injury in collegiate lacrosse, soccer, and basketball players: implications for anterior cruciate ligament mechanism and prevention." Am J Sports Med **34**(6): 899-904.

Miller, J. P., D. Sedory, et al. (1997). "Vastus medialis obliquus and vastus lateralis activity in patients with and without patellofemoral pain syndrome." J Sport Rehabil **6**: 1-10.

Mohr, K. J., R. S. Kvitne, et al. (2003). "Electromyography of the quadriceps in patellofemoral pain with patellar subluxation." Clin Orthop Relat Res(415): 261-71.

Moss, R. I., P. Devita, et al. (1992). "A Biomechanical Analysis of Patellofemoral Stress Syndrome." J Athl Train **27**(1): 64-69.

Piva, S. R., K. Fitzgerald, et al. (2006). "Reliability of measures of impairments associated with patellofemoral pain syndrome." BMC Musculoskelet Disord **7**: 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." J Orthop Sports Phys Ther **35**(12): 793-801.

Powers, C. M. (2003). "The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective." J Orthop Sports Phys Ther **33**(11): 639-46.

Powers, C. M., R. Landel, et al. (1996). "Timing and intensity of vastus muscle activity during functional activities in subjects with and without patellofemoral pain." Phys Ther **76**(9): 946-55; discussion 956-67.

Romano, C. and M. Schieppati (1987). "Reflex excitability of human soleus motoneurones during voluntary shortening or lengthening contractions." J Physiol **390**: 271-84.

Rose, H. M., S. J. Shultz, et al. (2002). "Acute Orthotic Intervention Does Not Affect Muscular Response Times and Activation Patterns at the Knee." J Athl Train **37**(2): 133-140.

Salsich, G. B., J. H. Brechter, et al. (2001). "Lower extremity kinetics during stair ambulation in patients with and without patellofemoral pain." Clin Biomech (Bristol, Avon) **16**(10): 906-12.

Sell, T. C., C. M. Ferris, et al. (2007). "Predictors of proximal tibia anterior shear force during a vertical stop-jump." J Orthop Res **25**(12): 1589-97.

Smith, A. D., L. Stroud, et al. (1991). "Flexibility and anterior knee pain in adolescent elite figure skaters." J Pediatr Orthop **11**(1): 77-82.

Souza, D. R. and M. T. Gross (1991). "Comparison of vastus medialis obliquus: vastus lateralis muscle integrated electromyographic ratios between healthy subjects and patients with patellofemoral pain." Phys Ther **71**(4): 310-6; discussion 317-20.

Tang, S. F., C. K. Chen, et al. (2001). "Vastus medialis obliquus and vastus lateralis activity in open and closed kinetic chain exercises in patients with patellofemoral pain syndrome: an electromyographic study." Arch Phys Med Rehabil **82**(10): 1441-5.

Taunton, J. E., M. B. Ryan, et al. (2002). "A retrospective case-control analysis of 2002 running injuries." Br J Sports Med **36**(2): 95-101.

Tumia, N., Maffulli, N (2002). "Patellofemoral Pain in Female Runners." Sports Medicine and Arthroscopy Review **10**(1): 69-75.

Witvrouw, E., R. Lysens, et al. (2000). "Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study." Am J Sports Med **28**(4): 480-9.