DIFFERENCES IN TRANSVERSE KNEE MOMENT IN HEALTHY, ACL-DEFICIENT, AND ACL-RECONSTRUCTED PATIENTS DURING STANDING TARGET MATCHING

by

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ABSTRACT

Anterior cruciate ligament (ACL) injury is a common injury affecting nearly 250,000 Americans a year (Boden et al. 2000). Reconstructive surgery costs add up to approximately $1.5 billion annually not including initial evaluation or post-operative rehabilitation (Boden et al. 2000). The anterior cruciate ligament (ACL) limits anterior tibial translation and internal tibial rotation and so in the absence of the ACL rotational instability is common. Transverse knee moment, which has not been the focus of much research, can determine ACL-deficient (ACL-d) subjects' ability or inability to compensate for this rotational instability. Target matching, both standing and seated, has provided insight for understanding neuromuscular control in both ACL deficient and reconstructed patients via EMG measurements (Williams et al. 2003; Macleod et al. 2011). We are now beginning to look at kinetic measures like transverse knee moment during this task in healthy, ACL-d and ACL reconstructed patients.

Therefore the first aim of this work was to investigate transverse knee moment measured during a neuromuscular task in a healthy population. There is no difference in transverse knee moment between the right and left limbs of healthy subjects during standing target matching. Additionally, the shear forces generated by the mobilizing limb strongly correlate with the transverse knee moment of the stabilizing limb. These results indicate kinetic measures produced during standing target matching are dictated by target matching role not the limb itself.

The second aim of this work was to evaluate transverse knee moment measured during a neuromuscular task in ACL-d patients. Our results show those with ACL injury have significantly higher internal rotation moments than healthy uninjured subjects. Increased rotational loads are present when subjects generate medial shear forces. This indicates an area of interest and the importance of joint stability in this medial direction.

The third and final aim of this work was to evaluate changes in transverse knee moment during a neuromuscular task in ACL reconstructed patients. In particular we tested subjects within six months to one year post reconstruction when re-injury risk is highest (Salmon et al. 2005; Paterno et al. 2012). From this study we found those who undergo ACL reconstruction produce higher internal rotation moments when compared to uninjured subjects. We also see increased rotational loading at medial targets. In our group of subjects it appears that increased rotational loading occurs after injury and is not mitigated by reconstruction.

The resulting increase in joint loading may have implications for high re-injury rates seen post reconstruction (Hewett et al. 2012) and high rotational loads have already correlated with increased cartilage loss (Henriksen et al. 2012). Producing force in a medial direction may be dangerous for those with ACL injury even after reconstruction and could be used to identify those at higher risk of re-injury. These results provide a basis to explore rotational loading corresponding to different graft types while exploring possible interventions to create joint stability in this medial direction.

Chapter 1

INTRODUCTION

ACL Injury and Rotational Instability

Anterior cruciate ligament (ACL) injury is a common injury affecting nearly 250,000 Americans a year (Boden et al. 2000). Reconstructive surgery costs add up to approximately $1.5 billion annually not including initial evaluation or post-operative rehabilitation (Boden et al. 2000). 70% of ACL injuries are noncontact (Boden et al. 2000). In video analysis of handball athletes noncontact ACL injury was most commonly caused by a combination of forceful valgus collapse and internal or external rotation with the limb near full extension (Olsen 2004). We can see two main components in noncontact ACL injury valgus collapse and internal/external rotation. Medial/lateral ground reaction force may be contributing to valgus collapse as it pushes the distal end of the tibia out from the body. Additionally noncontact injury can be related to the ACL's function as a major secondary restraint to internal rotation (Duthon et al. 2006; Boden et al. 2000). In the absence of this restraint rotational instability is common. Rotational loading and motion are key factors to injury and function of the ACL. Transverse knee moment, which has not been the focus of target matching research, can determine ACL-deficient (ACL-d) subjects' ability or inability to compensate for this rotational instability. These insights may guide rehabilitation efforts in promoting dynamic stability and increase understanding of the ACL's functionality.

After ACL rupture there are noted changes to internal and external rotation angles during gait. There is measured increased internal rotation during swing phase in those with ACL injury when compared to healthy subjects (Andriacchi & Dyrby 2005) and ACL-reconstructed patients (Georgoulis & Papadonikolakis 2003). Additionally the average position of the tibia was offset towards internal rotation throughout the gait cycle (Andriacchi & Dyrby 2005). The differences in rotation angle between healthy and ACL-d subjects can be translated to changes in kinetics, like transverse knee moment, as kinematics and kinetics are closely linked. Alterations to joint loading are known factors in the development of osteoarthritis and re-injury (Henriksen et al. 2012; Hewett et al. 2012). While the ACL is considered only a secondary restraint to internal rotation these results highlight the importance of this role in everyday activities.

Understanding Neuromuscular Control Post-Injury

Kinetic and kinematic measures including transverse knee moment have also been indicative of neuromuscular changes. Hip and knee kinematics measured during a drop vertical jump have been used to study ACL injury mechanisms and re-injury rates in female athletes (Hewett et al. 2006; Paterno et al. 2010). Transverse plane hip kinetics and kinematics along with sagittal plane knee moments correlated with re-injury rates while increased valgus and high abduction loads at the knee correlated with injury rates. It is important to note that Hewett et al. (Hewett et al. 2005), did not evaluate transverse moments at either the hip, knee, or ankle. With this in mind it would be advantageous to explore internal and external rotational moments of the knee in regards to neuromuscular control in the ACL-deficient population.

Alterations to neuromuscular control in ACL-d subjects can identify a subpopulation of patients that are eligible for non-operative care. Some of these alterations include differences in quadriceps strength and activation, and total support moment when comparing ACL injured patients who are and are not able to compensate for the rupture ligament (Rudolph et al. 1998; Rudolph et al. 2001). Additionally there are differences in EMG onset times for hamstring muscles (Rudolph et al. 2001). Pattern analysis of EMG revealed significantly different EMG patterns (Shiavi et al. 1992a) Standing target matching is a tool that has been used to understand neuromuscular control in those with ACL injury. In standing target matching subjects generate forces while standing to control a cursor on a screen and match that cursor with targets presented at various locations. One limb controls the cursor via visual feedback, the mobilizer, while the other limb, the stabilizer, maintains stability and is given no feedback. The mobilizer is required to produce shear forces in a number of different directions while minimizing the free moment. Being that target matching is a weight bearing task requiring both limbs and specific forces are constrained there is an inherent relationship between the mobilizing limb and stabilizing limb. With an explicit task goal, target location, data analysis is simplified. Investigating neuromuscular differences in the ACL injured population may further highlight patients with diminished functionally and stability post injury.

The high incidence of noncontact ACL injury is prevalent in a number of different sports including, basketball, Australian rules football, soccer, and handball (Orchard et al. 2001; Rochcongar et al. 2009; Boden et al. 2000; Olsen 2004). Noncontact ACL injury typically occurs during a deceleration or quick change in direction in the plant or landing limb. As mentioned previously noncontact ACL injury was most commonly caused by forceful valgus collapse of the limb near full extension in combination with internal or external rotation (Olsen 2004). Relating this to standing target matching the mobilizer limb is analogous to the plant or landing limb in that it is the leading limb which changes direction for the body, hence the limb of focus for these studies.

ACL Reconstruction

ACL reconstructive surgery is the current standard of care for those with ACL rupture with approximately 60% undergo reconstruction (Gobbi & Francisco 2006; Miyasaka et al. 1991). The main goal of ACL reconstruction (ACL-r) is to return patients to pre-injury levels of function and stability. Current reconstruction types include allograft, semitendinosus-gracilis graft, and bone-patellar tendon-bone graft. Bone-patellar tendon-bone grafts have higher morbidity (Feller & Webster 2003), kneeling discomfort, and decreased skin sensitivity when compared with hamstring reconstructions (Aglietti et al. 2005). While hamstring reconstruction shows higher knee laxity when compared to bone patellar bone graft (Barrett et al. 2002; Feller & Webster 2003).

Outcomes of reconstructive surgery are seen through changes in kinetics, kinematics, and neuromuscular control. During gait hamstring reconstruction has shown to mitigate aberrant knee rotations (Georgoulis & Papadonikolakis 2003). However, during downhill running ACL-r limbs have significantly higher external rotation and adduction when compared to uninjured limbs (Tashman 2004). During seated target matching voluntary muscle control increases from a pre-surgery level in patients who received hamstring grafts (Williams et al. 2005). Additionally, limb asymmetries in quadriceps strength, knee angle, and knee joint moment seen after injury show improvement 6 months after reconstruction continuing up to two years post-surgery (Roewer et al. 2011). Understanding ACL-r response to rotational loads may lend important information as another measure to determine reconstruction success as again there is little consensus on an optimal reconstruction method and rotational loading is rarely examined.

Rehabilitation Post Reconstruction

Neuromuscular training has been used as a rehabilitation tool in those who have undergone ACL reconstruction but also those who are eligible for non-operative care (Hewett et al. 2006; Paterno et al. 2010; Fitzgerald et al. 2000). Training programs are designed to enhance the muscle activity associated with ACL functionality with the ultimate goal of generating dynamic knee stability. These training protocols include treadmill speed training, foot agility exercises, multidirectional hops, and balance board training. Neuromuscular interventions have shown significant effect in reducing injury incidence rates in young athletes and female athletes (Hewett et al. 2006). These training protocols have also shown improvements in single-limb stability (Paterno et al. 2004) and star excursion balance test (Filipa et al. 2010). One such training protocol called perturbation training has shown improvements in inter-limb symmetry six months post ACL reconstruction (Hartigan et al. 2009) and six months post ACL injury (Di Stasi & Snyder-Mackler 2011). Additionally, perturbation training reduced muscle co-contraction in those with ACL rupture when compared to healthy subjects (Chmielewski et al. 2005).

With neuromuscular training yielding promising results the ability to evaluate the efficacy of these programs is important to understanding post-operative neuromuscular alterations. Standing target matching has the ability to do this and has already shown results in the ACL-d population. Seated target matching, a variation of standing target matching, found reduced muscle specificity in eight muscles in the ACL-deficient limb when compared to healthy limbs (Williams et al. 2003). While providing meaningful results seat target matching has limitations. First, seated target matching only considers each limb individually which may not be relatable to sports related tasks. Second, this is not a weight bearing task making us unable to evaluate joint loading. And so standing target matching is an ideal task to use in that we are able to evaluate joint loading in tasks similar to activities of daily living. Additionally standing target matching is a simplified motor control problem simplifying data analysis. As of yet the kinematic and kinetic outcomes of standing target matching have not been analyzed and these results can aid in design and evaluation of neuromuscular training.

Chapter 2

SPECIFIC AIMS

Rotational instability is a common effect of ACL injury as the ACL limits internal rotation (Duthon et al. 2006; Boden et al. 2000). To overcome rotational instability alterations to neuromuscular control are necessary. Understanding how ACL deficient subjects respond to rotational loads as pertaining to neuromuscular control can help identify compensation strategies. However it is difficult to directly evaluate ACL-deficient patients in internal and external rotational moments during similar dynamic tasks due to the risk of further injury.

A number of methods have been used to evaluate neuromuscular control in various settings. In particular, target matching, developed by Buchanan and colleagues, has been used to evaluate muscle activation strategies in ACL-deficient and ACL-reconstructed patients (Buchanan et al. 1986). Target matching has shown changes to neuromuscular control in ACL-deficient patients. Seated target matching found reduced muscle specificity in ACL-deficient patients when compared to healthy controls (Williams et al. 2004). Research regarding standing target matching has only looked at neuromuscular control as designated by electromyographic (EMG) activity. Because kinematics and kinetics can be considered the output of muscle activation joint moments is our variable of interest. Analysis of joint moments during standing target matching will also further elucidate stabilization mechanisms utilized by ACL-deficient and ACL-reconstructed patients and aid in guiding neuromuscular training efforts. The standing target matching task developed in our lab has the ability to challenge subjects in rotational loads in a safe and controlled manner. We can use this task to study healthy, ACL deficient, and ACL reconstructed patients. Additionally, results of this task can be used to aid neuromuscular training which has already proven successful in the ACL injured population (Hewett et al. 2006; Filipa et al. 2010; Paterno et al. 2004; Fitzgerald et al. 2000).

There are noted changes to internal and external rotation angles during gait and running in ACL-d and ACL-r when compared to healthy subjects (Chouliaras et al. 2009; Georgoulis & Papadonikolakis 2003; Andriacchi & Dyrby 2005). Because aberrant kinematics can influence kinetics it would be advantageous to explore internal and external rotational moments of the tibia resulting from standing target matching. Alterations to rotational loading conditions at the knee may increase the risk of osteoarthritis in an already high risk population (Henriksen et al. 2012). Potential changes could also indicate reduced stability in rotations, increasing the possibility of re-injury. With this in mind the ultimate goal of this work is to identify and understand ACL deficient and ACL reconstructed patient's response to internal/external rotational moments at the knee during a standing target matching task. To meet this end we must first characterize standing target matching in a healthy population to examine if side to side differences between limbs are negligible and then explore the transverse knee moment produced by ACL-d and ACL-r patients. For this project we have the following aims:

1. **Investigate transverse knee moment measured during a neuromuscular task in a healthy population**. Standing target matching constrains the free moment produced by the mobilizing limb, and in doing

so may have an effect on rotational loading of the knee. Additionally the stabilizing limb receives no feedback of the forces generated by that limb. From this we hypothesize:

Hyp 1.1: The limb acting as a stabilizer will exert a transverse knee moment as dictated by the shear forces generated by the mobilizer limb.

Hyp1.2: There will be no difference in the internal and external rotational moments between the right and left limb during the standing target matching. This will hold true when the right and left limb complete both roles of standing target matching, mobilizing and stabilizing.

2. **Evaluate transverse knee moment measured during a neuromuscular task in ACL-d patients.** Based on the role of the ACL as a major secondary restraint to internal tibial rotation we have the following hypothesis:

   Hyp 2.1: The transverse knee moment of the mobilizing limb in ACL-d subjects will be higher than that of healthy subjects.

3. **Evaluate changes in transverse knee moment during a neuromuscular task in ACL reconstructed patients.** ACL reconstruction seeks to return stability and function of the missing ACL owing to the following hypothesis:

Hyp 3.1: Transverse knee moment of the mobilizing limb during standing target matching in ACL reconstructed patients will be similar to that of healthy subjects because the passive restraint to internal rotation has been restored.

In the next chapter I will present results from Aim 1. Chapter four will include studies of ACL-d and ACL-r subjects for aims 2 and 3. A general summary will follow in chapter five.

Chapter 3

EVOLUTION OF TRANSVERSE KNEE MOMENT IN HEALTHY SUBJECTS DURING STANDING TARGET MATCHING

Introduction

Those with anterior cruciate ligament (ACL) injury show varied neuromuscular response, via differences in EMG, kinematics, and kinetics (Shiavi et al. 1992b; Rudolph et al. 1998; Rudolph et al. 2001). The varied responses can be indicative of increased or diminished stability and have allowed clinicians to identify those eligible for non-operative care and those with reduced stability. Understanding neuromuscular control in the ACL-deficient population may explain the etiology of increased or decreased stability seen in some post injury. Additionally, changes to neuromuscular control post reconstruction can be used to determine efficacy of the reconstruction. Target matching, both standing and seated, has provided insight for understanding neuromuscular control in both ACL deficient and reconstructed patients via EMG measurements (Williams et al. 2003; Macleod et al. 2011). We are just now starting to look at kinetics and kinematics during this task. However, before evaluating kinetics and kinematics of standing target matching in an injured population we must characterize it in a healthy population.

Target matching was originally used to understand neuromuscular control of elbow flexors and extensors (Buchanan et al. 1986). Target matching requires subjects to generate submaximal forces in a number of directions. These forces control a cursor on screen presented in front of the subject. Subjects are instructed to move the cursor to designated locations on the screen which is marked by a target. The subjects manage force production in a multitude of directions to successfully match the cursor within the target location. By designating the target location we are able to understand neuromuscular control by measuring electromyography, kinematics, and kinetics during the time while the subject is successfully placing the cursor in the target location.

Target matching for the upper extremities was later adapted for use in the lower limbs, but was limited to a single limb while the subject remained seated. Seated target matching was used to understand voluntary muscle control in ACL-d subjects and has provided valuable insight for this patient population. In this work EMG from ten muscles was collected during the seated target matching task and results showed reduced neuromuscular control in eight muscles of the ACL-d subjects when compared to both the uninjured limb and healthy control subjects; the vastus lateralis was the most affected muscle (Williams et al. 2003). Additionally the ACL-d subjects displayed increased global co-contraction (Williams et al. 2003). To be more relatable to dynamic tasks seated target matching was then modified for use during standing. In this modification one limb controls the cursor at a time. The limb actively controlling the cursor is called the mobilizing limb while the contralateral limb which maintains upright posture is called the stabilizing limb. From this design there is an inherent connection between the forces generated by each limb.

To control the cursor the mobilizing limb generates shear forces on a force plate. Additionally the mobilizing limb must minimize the free moment measured by the plate, which is not required of the stabilizing limb. During standing target matching subjects remain standing and to maintain static equilibrium the stabilizing limb must counteract all the forces the mobilizing limb is generating by creating equal and opposite forces. When considering shear forces the stabilizing must generate equal and opposite shear to the mobilizing limb, but when considering rotational loads this is not the case. As noted previously rotational loads produced by the mobilizing limb are limited by minimizing free moment. To maintain upright posture the stabilizing limb must compensate for what the mobilizing limb is unable to produce. This is important when considering the whole body as a global system, anterior or posterior shear caused by the mobilizer creates a moment about the whole body and because the subjects is required to keep their feet on the force plates at all times the stabilizing limb must create an internal joint moment to counteract this global moment.

The main goal of this work is to understand kinetic measures, specifically transverse knee moment, measured during standing target matching in a healthy population. Additionally we aim to characterize the standing target matching task for the healthy population to then use in the ACL-d and ACL-r patient groups. Due to the relationship between the mobilizing and the stabilizing limb, explained earlier, we hypothesize the average transverse knee moment of the stabilizing limb will significantly correlate to the anterior/posterior shear forces of the mobilizing limb. EMG measured from healthy subjects during standing target matching indicates no difference between right and left limbs when they are performing as both mobilizer and stabilizer. From this previous research we also hypothesize there will be no difference in the average transverse knee moment of the right and left limbs for healthy subjects. We believe this will occur when the right and left limb complete both roles, mobilizer and stabilizer.

Methods

Subjects & Target Matching

This study included eight healthy subjects (4 men, 4 women) with no history of knee injury (mean ± SD; age = 22.9 ± 3.0 yrs, mass = 77.5 ± 14.5 kg, BMI = 25.0 ± 3.1 kg/m^2). All subjects were regular participants in (> 50 hrs/year) level I and II sports requiring running and cutting. Subjects stood barefoot approximately hip-width apart on two force plates, a separate force plate for each foot (OR-6, AMTI, Watertown, MA, USA). One foot was selected at random to control a cursor and was coined the *mobilizer*. The limb not controlling the cursor but still maintaining stability for the subject was coined the *stabilizer*. Anterior/Posterior and Medial/Lateral shear forces controlled the cursor's movement in the anterior-posterior-medial-lateral plane respectively. The free moment from the force plate, controlled a needle on the cursor which rotates both clockwise and counterclockwise. A projector was used to display the cursor on a screen in front of the subject to provide visual feedback of the subjects' shear and rotational forces. The standing target matching task required subjects to position the cursor, described earlier, on a target consisting of two concentric circles using the mobilizing limb while kinematic and force plate measurements were taken from both the stabilizing and mobilizing limb. Targets appeared one at a time on the screen at one of eighteen positions around a circle, located at 20° increments in the anterior-posterior-medial-lateral plane (Figure 3.1). Subjects were required to hold the cursor within the narrow target for 500 ms before the trial was considered successful. 72 targets were matched bilaterally (each limb performs the mobilizer task). Target location from the center of the screen was designated as 50% of the weakest maximum voluntary contraction of the mobilizing limb, collected prior to trials in the anterior, posterior, medial and lateral directions. Additionally, the mobilizing limb was required to minimize internal/external rotations loads by maintaining the needle in a narrow region of the cursor corresponding to 10% of maximum internal/external rotation, again measured by the free moment. Lastly, subjects received no visual feedback of force generation of the stabilizing limb.

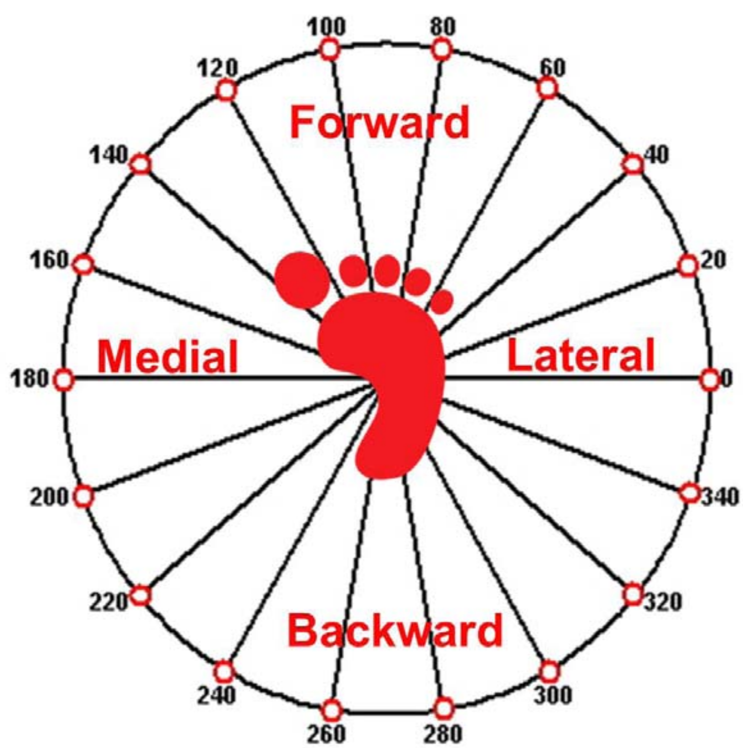

Figure 3.1 Target position from perspective of the right limb.

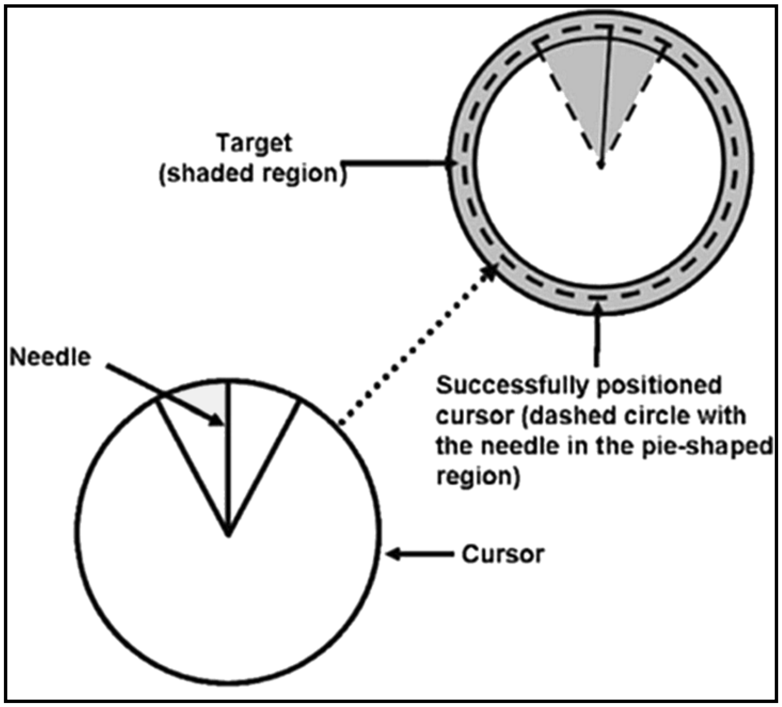

Figure 3.2 Depiction of cursor (lower left) and target (upper right). Successful match is also shown in upper right.

Data Collection

Ground reaction force (GRF) data was collected via two force plates at 1000 Hz. Motion capture data was collected at 50 Hz via an 8 camera system (Qualysis Motion Capture System, Gothenburg, Sweden). Retro-reflective markers were placed on the subjects' anatomical landmarks. Additionally markers adhered to rigid shells were placed on the thighs and shanks of subjects to track motion of the lower limbs.

Data Processing

GRF and motion data were used to calculate transverse knee moment. Ground reaction force data was filtered using a 4^{th} order low pass Butterworth filter with a frequency cutoff of 50 Hz. Motion data was filtered with a 4^{th} order low pass Butterworth filter with a frequency cutoff of 6 Hz. Transverse knee moment for both limbs was calculated in Visual 3D using both GRF and kinematic data collected during the 500 ms period the cursor was located in the target. The 500 ms period was indicated by +2.5 V peak that was synced with the motion and GRF data. Moments calculated for the left limb were transformed into the reference frame of the right limb for direct comparison at each target position.

Results

There was no significant difference in average transverse knee moment between the right and left limbs of healthy subjects when acting as the either mobilizer or the stabilizer (Figures 3.3 & 3.4). Additionally the AP shear generated by the mobilizing limb significantly correlated to the average transverse knee moment (TKM) of the stabilizing limb (Figure 3.5, $p<0.05$). Our regression analysis has an R^2 value of 0.74.

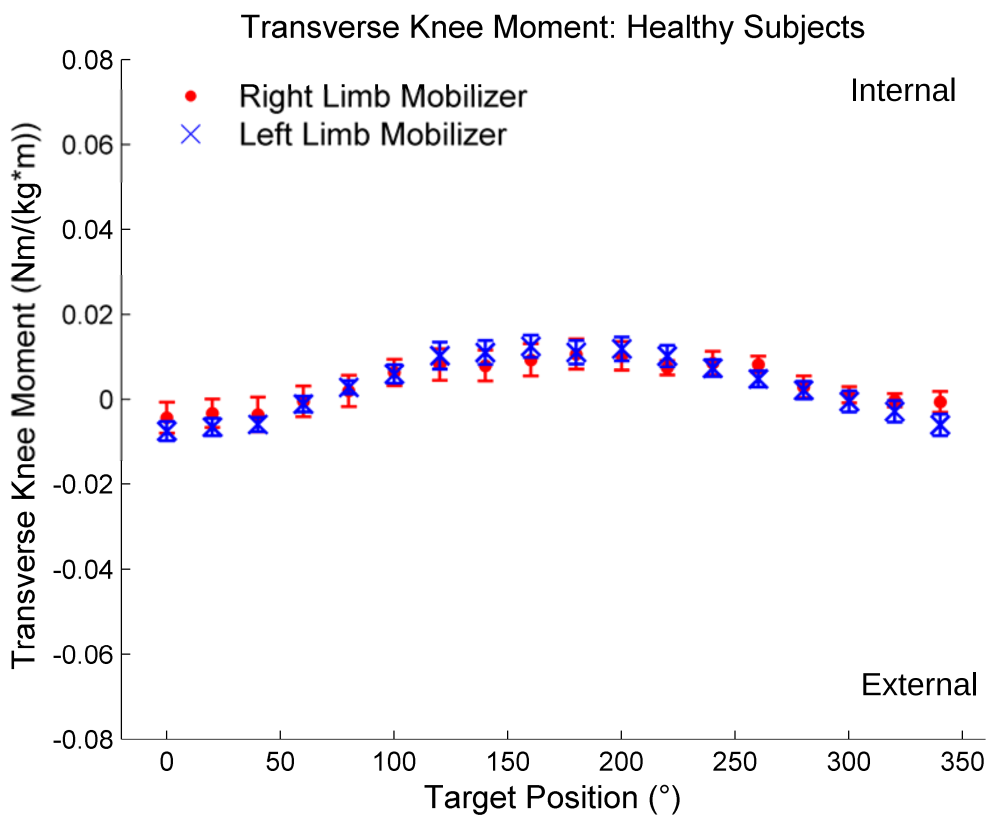

Figure 3.3 Average transverse knee moment ± standard error normalized to body mass*height of the **mobilizing** limb in healthy subjects, right & left limb. Internal rotation moment is positive and external rotation moment is negative.

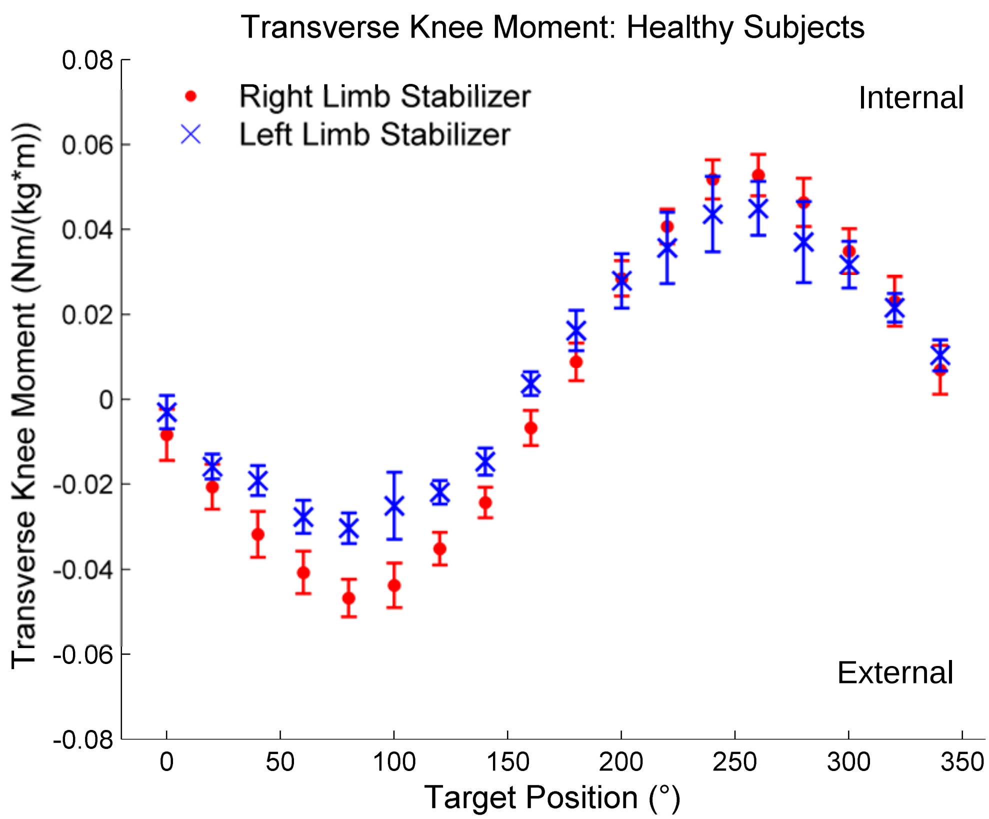

Figure 3.4 Average transverse knee moment ± standard error normalized to body mass*height of the **stabilizing** limb in healthy subjects' right & left limb. Internal rotation moment is positive and external rotation moment is negative.

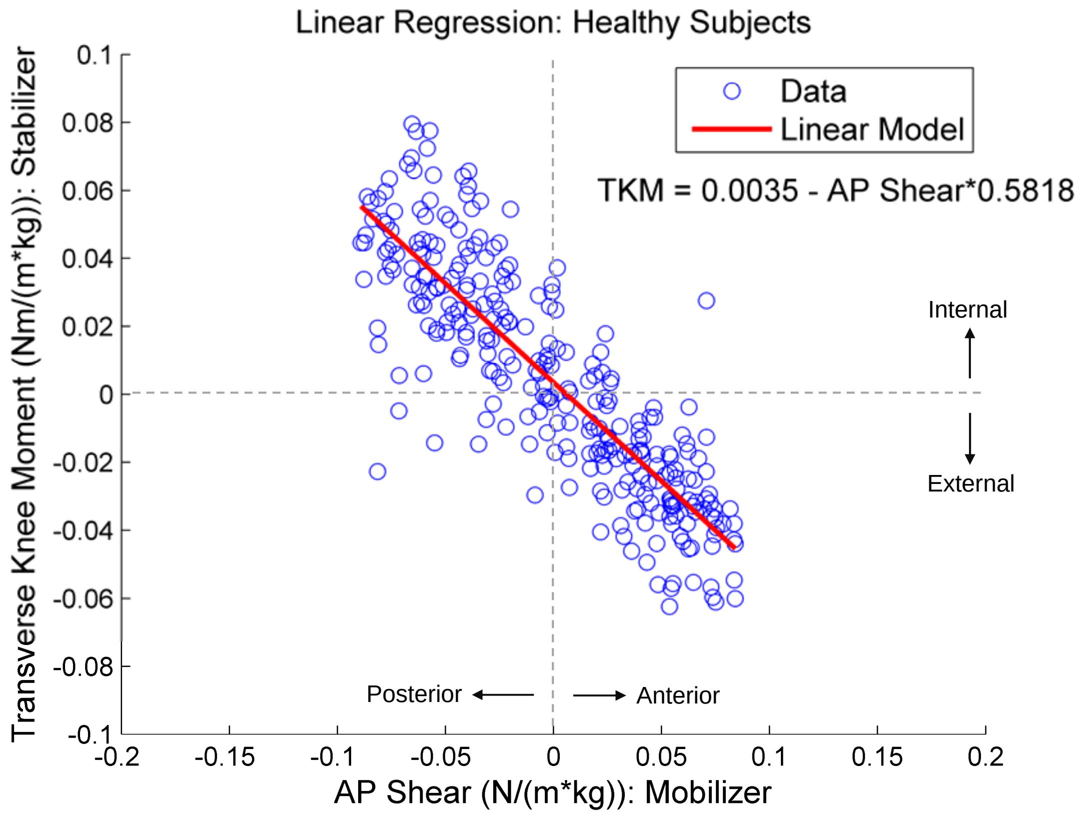

Figure 3.5 Linear model of the AP shear from the mobilizing limbs vs. average transverse knee moment of the stabilizing limbs normalized to body mass*height in healthy subjects. (R^2=0.74, p-value <0.05)

Discussion

Overall our results support both of our hypotheses. The shear forces generated by the mobilizing limb strongly correlate with the transverse knee moment of the stabilizing limb. Specifically as the mobilizing limb generates shear force in the anterior direction the stabilizing limb generates external rotation moments. Conversely, as the mobilizing limb generates posterior shear forces the stabilizing creates an internal rotation moment. This correlation is evident in the sinusoidal pattern seen in the transverse knee moment of the stabilizing limb (Figure 1.4). There is a peak internal rotation moment at target positions requiring posterior shear force and a peak external rotation moment at target positions requiring anterior shear force.

There is no difference in transverse knee moment between the right and left limbs of healthy subjects during standing target matching. While there is a distinct difference between the transverse knee moment produced when mobilizing versus when stabilizing, the right and left limbs perform the stabilizing task similarly and the right and left limbs perform the mobilizing task similarly. These results indicate kinetic measures produced during standing target matching are dictated by target matching role not the limb itself. Studies measuring electromyography during standing target matching support our findings. EMG from seven muscles was collected during the standing target matching task using healthy active subjects to understand muscle activation patterns specific to the muscle but also specific to task (mobilizer vs. stabilizer). This study found that neuromuscular control differences were based on limb task not dominance, with the lateral and medial hamstrings showing a significant difference in neuromuscular control, as measured by muscle specificity, when performing different tasks (MacLeod 2012).

Target matching is an ideal task to use for understanding neuromuscular control. The task goal is explicit allowing us to make meaningful conclusions about neuromuscular control. Because the standing target matching requires subjects to maintain upright posture and use both limbs it can also be related to everyday tasks. However, there are some limitations in this study. Our sample size is small, but power analysis for tests made at the medial target positions indicates we have an appropriate number of participants. Another limitation of this study is that only foot position was constrained during testing. Other joints were unconstrained and resulted in subjects using a wide variety of body positions to generate the appropriate amount of force. When have yet to look at the kinematics produced during standing target matching.

These results have important implications moving forward. First, we see no difference between the right and left limb during the standing target matching task as measured by transverse knee moment. From this work any difference in transverse knee moment measured from those with ACL rupture or ACL reconstruction may be related to the injury or surgery itself. Additionally, the results of this study indicate the standing target matching task challenges both right and left limbs equally. The strong correlation between the shear forces generated by the mobilizing limb and transverse knee moment of the stabilizing limb highlight the importance of using standing target matching; one limb is able to influence the joint moments of the other limb. In future studies we plan to move forward exploring how those with ACL injury and reconstruction complete this task.

Chapter 4

ARE INTERNAL-EXTERNAL ROTATIONAL MOMENTS IN ACL DEFICIENT AND ACL RECONSTRUCTED SUBJECTS DIFFERENT THAN THOSE IN HEALTHY SUBJECTS?

Introduction

Rupture of the anterior cruciate ligament (ACL) affects nearly 250,000 Americans per year (Boden et al. 2000). Those with ACL injury will mostly undergo reconstructive surgery which costs approximately $1.5 billion annually not including initial evaluation or post-operative rehabilitation (Boden et al. 2000). ACL injury is prevalent in a number of different sports including soccer, basketball, Australian rules football, and handball (Serpell et al. 2011; Orchard et al. 2001; Boden et al. 2000; Rochcongar et al. 2009; Olsen 2004).

The anterior cruciate ligament (ACL) limits anterior tibial translation and internal tibial rotation. In healthy subjects tibial rotation causes both cruciate ligaments of the knee to twist on each other tightening the joint and so in the event of a rupture we have rotational instability (Duthon et al. 2006; Boden et al. 2000). Episodes of giving way, common in the ACL injured population, highlight this instability. Additionally, there is a high prevalence of knee osteoarthritis in those with previous ACL rupture (Noyes et al. 1983). Currently knee adduction measures (joint moments and angles) predict OA progression (Miyazaki 2002; Sharma et al. 1998). Transverse knee moment (TKM), which we define as the internal joint moment in the transverse plane correlates with increased cartilage loss but can also capture rotational instability (Henriksen et al. 2012). This measure lacks investigation and further understanding of rotational instability may guide rehabilitation efforts to promote dynamic stability which may prevent injury and re-injury. Additionally measuring transverse knee moment during standing target matching can provide insight into the ACL's functionality potentially providing support for different intervention therapies.

Studies have shown that kinetic and kinematic measures, like that of transverse knee moment, are indicative of neuromuscular control. Transverse plane hip kinetics and frontal plane knee kinematics during a drop vertical jump were able to predict re-injury rates in athletes (Paterno et al. 2010). Additionally neuromuscular training aimed at these measures were able to reduce injury rates in female athletes (Hewett et al. 2006). Individuals have varied neuromuscular response to ACL injury as measured by kinetics, kinematics, and electromyography (Shiavi et al. 1992b; Rudolph et al. 1998; Rudolph et al. 2001). These different neuromuscular responses have identified subjects eligible for non-operative care and those with increased instability. Evaluating neuromuscular control in those with ACL injury can guide retraining efforts and further identify those who may or may not need reconstruction.

The most common treatment for ACL injury is reconstructive surgery, 60% of those injured will undergo reconstruction (Gobbi & Francisco 2006; Miyasaka et al. 1991). ACL reconstruction aims to return patients to pre-injury levels of function and stability. Current reconstruction types include allograft, semitendinosus-gracilis graft, and bone-patellar tendon-bone graft. While all graft types are successful in returning patients to a functional state, there are still deficits that need to be addressed. Within the first year after surgery approximately two thirds of athletes do not return to competitive sports (Ardern et al. 2011). Risk of re-injury is highest in this first year after the initial reconstruction (Paterno et al. 2012; Salmon et al. 2005) and of those which return to activity 20-25% will experience a second knee injury (Hui et al. 2011). Astonishingly, female athletes who have already undergone ACL reconstruction are 4 to 15 times more likely to have a second ACL rupture than healthy uninjured athletes (Paterno et al. 2012; Hewett et al. 2005). Alterations to joint kinetics, joint kinematics, and neuromuscular control have all been indicated as contributors to re-injury (Hewett et al. 2012). Up to one year post reconstruction is a crucial time period and understanding neuromuscular control during this time is vital to preventing further injury; for our study we will be testing subjects 6 months to one year post reconstruction in hopes of identifying important neuromuscular changes that may be able to discriminate ACL-d and ACL-r subjects potentially at higher risks for re-injury.

It is important to note ACL reconstruction has been shown to improve a number of different measures including quadriceps strength, sagittal plane knee angle, sagittal plane knee moments, however there is little known about how well reconstruction affects rotational loads (Roewer et al. 2011). ACL reconstruction also reduces abnormal knee rotations during gait (Georgoulis & Papadonikolakis 2003) but not downhill running (Tashman 2004) when compared to uninjured limbs. Lastly, during seated target matching voluntary muscle control improved in most muscles following ACL reconstruction with hamstrings graft (Williams et al. 2005). ACL reconstruction that improves joint loading in both translations and rotations would be ideal. Understanding rotational loads in reconstructed patients can aid in designing potential grafting methods.

With ACL deficient and reconstructed populations dynamic rotational loads risk further or re-injury any neuromuscular testing must be done in a controlled, safe, but still challenging setting. ACL-d and ACL-r subjects are restricted from certain tasks deemed unsafe, with one task being a crossover cut. A crossover cut is completed by planting the stance foot and crossing the contralateral limb over it providing acceleration in the running direction (Nyland et al. 1999). In a hamstrings fatigue model, healthy subjects showed decreased transverse plane knee control at initial impact during crossover cuts (Nyland et al. 1999). Another study found minimal hamstrings activation and high quadriceps activation just before footstrike in healthy subjects in a variety of cutting and stopping maneuvers including a crossover cut this imbalance in activation may be placing undue stress on the ACL (Colby et al. 2000). While research regarding cross over cutting in a healthy population has provided meaningful insight into injury mechanisms asking ACL-d and ACL-r subjects to perform this task is dangerous. In an effort to still have ACL-d and ACL-r subject produce meaningful rotational loads our lab has developed a task called standing target matching that can be used to understand neuromuscular control in a safe an effective manner (Buchanan et al. 1986; Macleod et al. 2011). Standing target matching requires subjects to generate controlled submaximal shear forces with both limbs while standing. With these submaximal shear forces one limb controls a cursor, the mobilizing limb, while the contralateral limb maintains upright posture, the stabilizing limb. This task requires subjects to successfully place the cursor at specified locations on the screen.

The overall goal of this study is to understand rotational loads in subjects with ACL injury and reconstruction during a neuromuscular control task. Utilizing the standing target match we can have subjects generate rotational loads safely. As mentioned earlier the ACL limits internal tibial rotation; the absence of this restraint may lead to increases in internal rotation. The combination of increased internal rotation and poor muscular control (Macleod et al. 2011) seen in those with ACL injury and outcomes seen post reconstructive surgery lead to the following hypotheses: ACL-d subjects will exhibit higher transverse knee moments when compared to healthy control subjects and transverse knee moment measured in those with ACL reconstruction will be similar to that of healthy, uninjured subjects.

Methods

Subjects

There were 24 subjects total for this study; 8 healthy controls (4 men, 4 women), 8 ACL deficient (ACL-d) subjects (4 men, 4 women), and 8 ACL reconstructed (ACL-r) subjects (5 men, 3 women). It is important to note ACL-d and ACL-r subjects are not the same subjects as not all ACL-d subjects were able to return post reconstruction. Healthy controls were active in at least 50 hours per year of level I & II sports which include running and cutting tasks (mean ± SD; age = 22.9 ± 3.0 yrs, mass = 77.5 ± 14.5 kg, BMI = 25.0 ± 3.1 kg/m^2). Preliminary data indicates there is no difference between the transverse knee moment of healthy right and left limbs when completing standing target matching and so our results for healthy subjects include the average of the right and left limb. ACL-d subjects had complete isolated rupture of the ACL within six months of testing (mean ± SD; age = 27.8 ± 9.7 yrs, mass = 73.1 ± 16.1 kg, BMI = 25.4 ± 5.8 kg/m^2). ACL rupture was confirmed with MRI and/or side to side knee laxity greater than 3 mm. ACL-r subjects received either semitendonosus-gracilis graft or allograft (mean ± SD; age = 21.1 ± 3.4 yrs, mass = 73.0 ± 14.6 kg, BMI = 25.1 ± 5.9 kg/m^2). Reconstruction was confirmed with MRI and subjects were tested within 1 year of reconstruction. Subjects were excluded from the study if they had any of the following: previous ACL injury, concomitant ligament pathology, unresolved fracture, greater than trace effusion, pain with a single hop, quadriceps lag, and hip or ankle pathology.

Target Matching

Subjects stood barefoot on two force plates (OR-6 AMTI, Watertown, MA, USA) and foot position was constrained throughout testing. To constrain foot position subjects were asked to stand comfortably with feet hip width apart and toes pointing forward the feet were then traced on the force plate. Subjects generated shear forces on two separate force plates. The shear forces generated by a single limb controlled a cursor presented on a screen in front of subjects (Figure 4.1). The cursor consisted of a circle with a wedge and needle within the circle. The single limb controlling the cursor was called the mobilizer, while the contralateral limb was called the stabilizer. The goal of standing target matching was to place the cursor inside of the target (Figure 4.2). The target consists of two concentric circles and also appeared on the screen in front of subjects. It appeared at 20° increments around a circle (Figure 4.1). When matching targets subjects must consider four constraints; position of the target on the screen, size of the target, needle position in the cursor, and time. Target position on the screen was determined by MVC taken prior to testing. The distance from the center of the screen to the target was 50% of the minimum MVC of four primary directions which include Anterior/Forward, Posterior/Backward, Medial, and Lateral. Cursor size was controlled by weight distribution. To fit the cursor within the two circles of the target subjects must evenly distribute weight on both feet. The needle on the cursor responded to rotational loads. The wedge denoted 10% of the rotational MVC taken prior to testing. A successful match required the needle stay within the wedge. Lastly subjects must maintain a correctly placed cursor within the target for 500 ms. In review subjects controlled shear forces to reach the target location, weight distribution to fit cursor inside the target, rotational loads to keep the needle in the wedge, and timing when completing the target matching protocol.

Statistical Testing

Statistical testing included independent t-tests comparing the transverse knee moment of the mobilizing limb averaged during the 500 ms period the cursor was successfully placed within the target. Initially four t-tests were conducting each corresponding to a primary shear direction. For the forward/anterior direction the average TKM from target positions 80° and 100° were averaged and used for statistical testing. For the backward/posterior direction the average TKM from target positions 260° and 280° were averaged and used for statistical testing. For the medial and lateral directions average TKM from the 180° and 0° positions, respectively, were used for statistical testing. If any t-tests for the four primary shear directions indicated a significant difference the surrounding targets were then tested. A significance level of 0.05 was used for all tests.

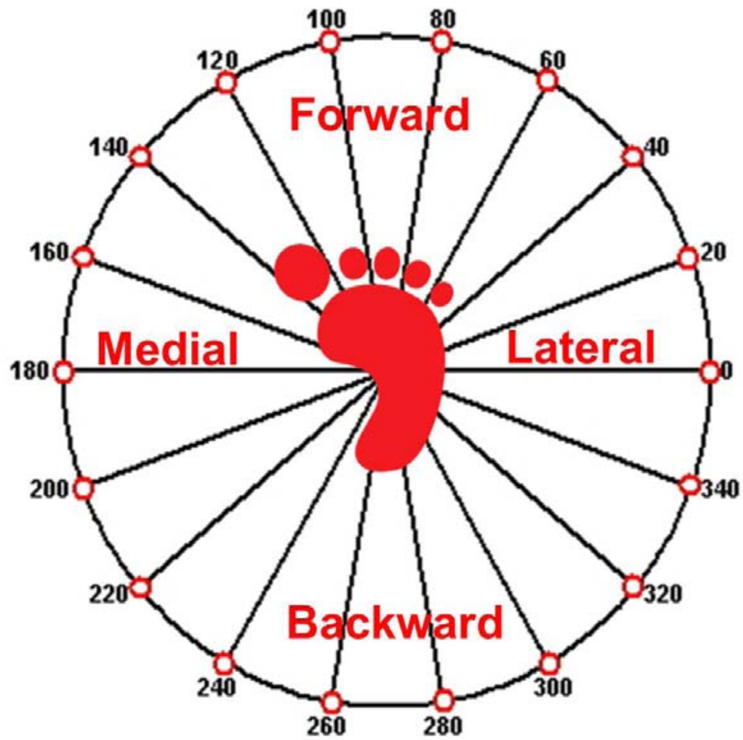

Figure 4.1 Target position from perspective of the right limb.

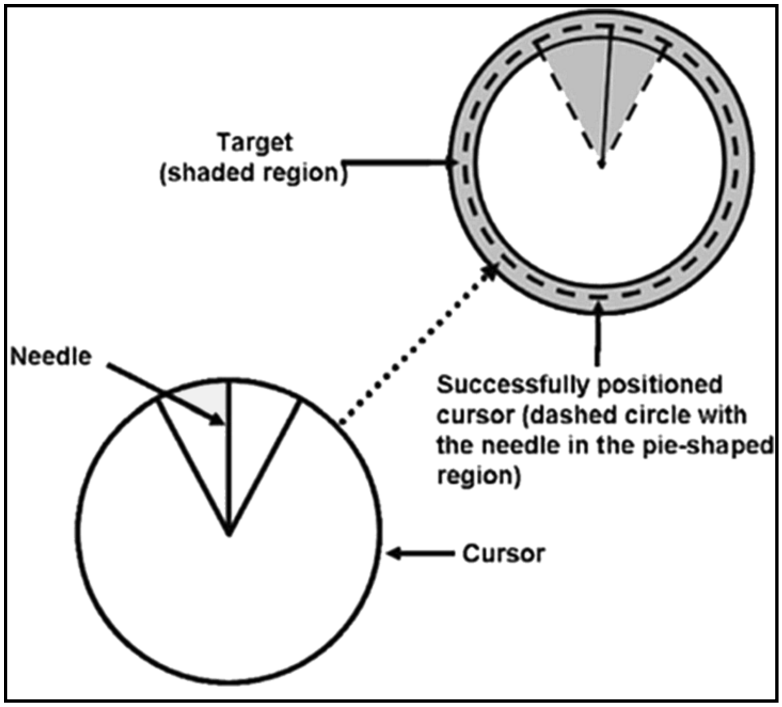

Figure 4.2 Depiction of cursor (lower left) and target (upper right). Successful match is also shown in upper right.

Results

We found that when acting as the mobilizer ACL injured limbs have significantly larger transverse knee moment when compared to limbs of healthy control subjects (Figure 4.3, $p<0.05$). Specifically the ACL-d limbs have greater internal rotation moment at five target positions. These differences occur at target positions requiring mostly medial shear forces (140°-220°).

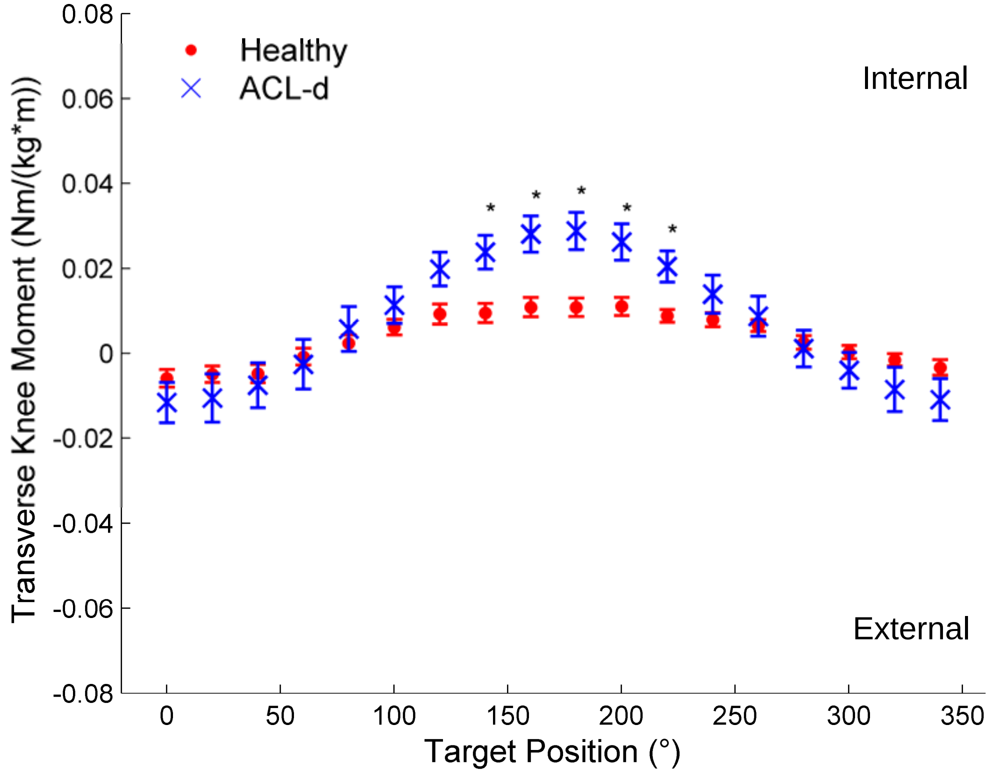

Figure 4.3 Average transverse knee moment ± standard error normalized to body mass*height of the **mobilizing** limb in ACL-d and healthy subjects. Internal rotation moment is positive and external rotation moment is negative. * $p<0.05$

Additionally ACL reconstructed limbs also have significantly larger transverse knee moment when compared to limbs of healthy control subjects when the acting as the mobilizer (Figure 4.4, $p<0.05$). As seen in ACL injured subjects the ACL reconstructed subjects have greater internal rotation moments at target positions requiring mostly medial shear forces (140°-220°).

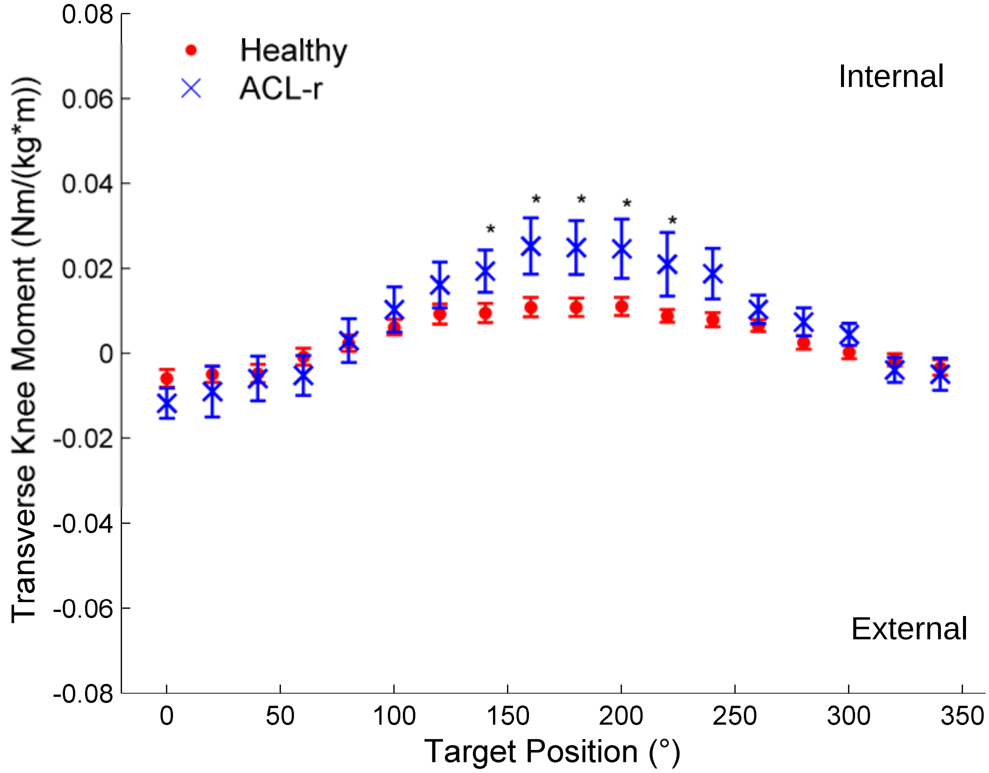

Figure 4.4 Average transverse knee moment ± standard error normalized to body mass*height of the **mobilizing** limb in ACL-r and healthy subjects. Internal rotation moment is positive and external rotation moment is negative. * $p<0.05$

Discussion

Our results support our first hypothesis but not our second hypothesis. That is we observed higher transverse knee moment in ACL-d patients, but did not find significant changes in ACL-r patients when compared to healthy controls. First, those with ACL injury have significantly higher internal rotation moments than healthy uninjured subjects. While those who undergo ACL reconstruction also produce higher internal rotation moments when compared to uninjured subjects. The difference in transverse knee moment between uninjured, ACL-d, and ACL-r subjects occurs when subjects generate mostly medial shear force, highlighting an area of interest. The difference in transverse knee moment has important implications for further injury and osteoarthritis.

As mentioned previously, high transverse knee moment correlates with increased cartilage loss (Henriksen et al. 2012). As patients return to sports requiring running and cutting they will be required to generate shear forces in a multitude of direction including the medial direction. For example as players land from a jump and subsequently change direction they may generate medial shear force with the plant limb as they run to complete the next task. This motion can be seen in basketball after shooting and then returning on defense or in soccer as players often receive the ball from the air, land then subsequently continue on foot in the direction of the ball. In both soccer and basketball athletes must land and quickly run in the necessary direction but must also maneuver other players while competing for ball possession or field position. Athletes may be experiencing medial shear forces multiple times during a game putting them at risk for injury or re-injury and increasing their risk for the development of osteoarthritis.

70% of all ACL injuries are caused by a noncontact mechanism (Boden et al. 2000). Noncontact injury is common in a wide range of sports including basketball, Australian rules football, soccer, and handball (Serpell et al. 2011; Orchard et al. 2001; Rochcongar et al. 2009). Video analysis of female handball athletes indicated that the most common cause of noncontact injury was a combination of a forceful valgus collapse and internal or external rotation with the limb near full extension (Olsen 2004). Referring to valgus collapse medial shear forces may be a contributor as it would push the distal end of the shank out from the body increased rotational loading at medial targets further support this idea. Additionally, valgus loading of the knee is strong predictor of injury and re-injury in female athletes (Hewett et al. 2005). Kinematic data indicate a peak in abduction angle of the tibia at the medial target positions, where we also see large internal rotation moments in ACL-d and ACL-r subjects. Increased internal rotation moments and the peak in abduction angle at the medial targets indicate standing target matching may be able to create similar ACL injury mechanisms while still maintaining low magnitude joint loads as to prevent injury strengthening conclusions made from this work.

Results found in gait analysis support our findings in standing target matching. These studies have found differences in rotation angles. There is measured increased internal rotation during swing phase in those with ACL injury when compared to healthy subjects, additionally the average position of the tibia was offset towards internal rotation throughout the gait cycle (Andriacchi & Dyrby 2005). As kinematics and kinetics are closely linked the increased internal rotation moment we see in ACL-d patients is expected. When looking at patients post reconstruction abnormal rotations during gait are no longer present, however this is not the case in more demanding tasks like downhill running. As standing target matching is a low demand task one would assume the rotational moments would be similar to healthy uninjured subjects. Our results show this is not the case. Studies evaluating reconstruction efficacy mostly explore sagittal plane motion and loading with little work in transverse plane measures. Rotational loading may lend additional insight in ACL reconstruction methods.

We are able to conclude that standing target matching is a safe and effective task for those with ACL injury. No subjects reported pain or were injured during testing. Standing target matching is an ideal task as it requires both limbs as most sports related tasks do but is also a simplified neuromuscular control task with clear task objective. However it is important to address limitations of this study. Our sample size is small, but power analysis focusing on comparisons made at the medial target positions indicates our sample size is sufficient. Another limitation of this study is that only foot position was constrained during testing. Other joints were free to move and resulted in subjects using a wide variety of body positions to generate the appropriate amount of force.

Producing force in a medial direction is associated with increased rotational moments and this may be dangerous for those with ACL injury and even after reconstruction. These results can be used to guide rehabilitation with one example being perturbation training. The goal of perturbation training is to improve muscle sensitivity to create joint stability. To achieve this therapists apply controlled forces in different directions while subjects stand on perturbing surface. Regarding ACL deficient and reconstructed patients perturbation training has shown to be very successful. Perturbation training improves inter limb symmetry in both ACL injured and reconstructed patients (Di Stasi & Snyder-Mackler 2011; Hartigan et al. 2009). Perturbation training also reduces muscle co-contraction post ACL reconstruction (Chmielewski et al. 2005). By manipulating the direction of force application this training can be modified to emphasize joint stability in the medial direction to overcome these high loads at medial targets

Overall, ACL-d subjects have higher internal rotational moments compared to healthy uninjured subjects and this persists after reconstruction. These results have implications for osteoarthritis as high transverse knee moment correlates with cartilage loss (Henriksen et al. 2012). Current research on gait in those with ACL injury support our results. Regarding those with ACL reconstruction we can say that current surgical methods may not be compensating for alterations to rotational loading indicating risk for re-injury. Perturbation training is a potential tool to emphasize medial stability in those with injury and post reconstruction. Additionally future work comparing transverse knee moment from different graft types may indicate an optimal surgical method.

Chapter 5

CONCLUSIONS

The overall goal of this work was to identify and understand ACL deficient and ACL reconstructed patient's response to standing target matching as measured by internal/external rotational moments at the knee.

The purpose of aim 1 was to investigate transverse knee moment measured during standing target matching in a healthy population. We had two hypotheses:

> **Hyp 1.1**: The limb acting as a stabilizer will exert a transverse knee moment as dictated by the shear forces generated by the mobilizer limb.
>
> **Hyp1.2**: There will be no difference in the internal and external rotational moments between the right and left limb during the standing target matching. This will hold true when the right and left limb complete both roles of standing target matching, mobilizing and stabilizing.

Our results support both hypotheses. There was no difference in the average transverse knee moment of healthy limbs. This occurs when the limb is acting as a mobilizer or a stabilizer. Additionally, there was a strong and significant correlation between the AP shear of the mobilizing limb and the transverse knee moment of the stabilizing limb. The conclusions from this first aim indicate any differences in transverse knee moment between healthy and ACL deficient patients can be attributed to the injury.

In aim 2 we identified differences in average transverse knee moment between healthy and ACL deficient patients. We hypothesized the following:

Hyp 2.1: The transverse knee moment of the mobilizing limb in ACL-d subjects will be higher than that of healthy subjects.

Results from this work support the hypothesis presented above. We found that those with ACL injury have higher internal rotation moment than healthy subjects at target positions requiring mostly medial shear forces. Increased rotational loading has implications for the progression of osteoarthritis which is common in those with ACL injury. With differences in transverse knee moment occurring at targets requiring mostly medial shear force we have identified an area of interest emphasizing the importance of medial stability.

Finally in aim 3 we studied transverse knee moment in those who have undergone ACL reconstruction. We hypothesized:

Hyp 3.1: Transverse knee moment of the mobilizing limb during standing target matching in ACL reconstructed patients will be similar to that of healthy subjects because the passive restraint to internal rotation has been restored.

The results from this study do not support this hypothesis. Post reconstruction subjects with ACL reconstruction have significantly higher internal rotational moments when compared to healthy subjects which occur at target positions requiring medial shear forces, virtually identical to what is seen in ACL injured subjects. The results from our group of subjects evaluated for Aim 3 indicate that reconstructive surgery may not provide the proper restraint during rotational loading.

The results from this work provide greater understanding of the ACL's role under rotational loading. It has been well established that the ACL is a major restraint to anterior tibial translation and there is much research evaluating translations of the tibia, however this is not the case for research regarding rotational loading of the tibia. These results indicate a need for further research in this area. The combination of reduced neuromuscular control and proprioception in rotational movements commonly seen after ACL injury may be creating an environment that produces the higher internal rotational moments seen during the standing target matching. The resulting increase in joint loading may have implications for high re-injury rates seen post reconstruction (Hewett et al. 2012) and high rotational loads have already correlated with increased cartilage loss (Henriksen et al. 2012).

Additionally the standing target matching task sufficiently challenges subjects in rotational loading without risking further injury as no subjects reported pain or adverse results as a consequence of the standing target matching task. We have identified standing target matching as a suitable task that can be used in understanding neuromuscular control for those with ACL injury and subsequent reconstruction. Most importantly we have identified rotational loading as an important measure to consider for rehabilitation in subjects post ACL injury and reconstruction. From these studies we will begin exploring possible interventions to prevent the increased rotational loads by emphasizing medial stability, particularly using perturbation training. Additionally we will explore rotational loading changes depending on graft type.

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Appendix A

HUMAN SUBJECTS REVIEW BOARD APPROVAL

HUMAN SUBJECTS REVIEW BOARD ACTION
University of Delaware
Newark, DE 19716

DJB

Protocol title: **ACL Injured Knee: MRI and biomechanical Modeling**

Principal investigator(s): **Thomas Buchanan, PhD – Mechanical Engineering**

HSRB number: **HS 09-071 (renewal of HS 08-071)**

Type of review: ☐ Expedited ☒ Full Board

The Human Subjects Review Board has reviewed the above-referenced protocol with respect to (1) the rights and welfare of the subjects: (2) the appropriateness of the methods to be used to secure informed consent; and (3) the risks and potential benefits of the investigation, and has taken the following action:

☒ Approved without reservation

☐ Approved as revised on original document.

☐ Disapproved for reasons noted below

Approval date: **September 17, 2008**

Approval period: **One Year**

Expiration date: **September 18, 2009**

Submittal date for continuing review: **August 18, 2009**

Changes in the protocol must be approved in advance by the HSRB.

Comments:

9-23-08
Date

Thomas M. DiLorenzo, Ph.D.
Chair, Human Subjects Review Board
210 Hullihen Hall
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DATE:	September 7, 2012
TO:	Thomas Buchanan, PhD
FROM:	University of Delaware IRB
STUDY TITLE:	[128521-7] ACL Injured Knee: MRI and Biomechanical Modeling
SUBMISSION TYPE:	Continuing Review/Progress Report
ACTION:	APPROVED
APPROVAL DATE:	September 7, 2012
EXPIRATION DATE:	September 17, 2013
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category # 9

Thank you for your submission of Continuing Review/Progress Report materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.