AN ABSTRACT OF THE THESIS OF

<u>Roy Almog</u> for the degree of <u>Honors Baccalaureate of Science in Exercise and Sport</u> <u>Science presented on June 2, 2015</u>. Title: <u>The Influence of Knee Extension Rate of</u> <u>Torque Development on Sagittal Plane Knee Biomechanics during Landing.</u>

Abstract approved:

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Abstract Body

Purpose: To investigate the influences of RTD on biomechanical factors upon landing. **Methods:** A nine camera motion capture system (Vicon, Inc.) was used with standard retroreflective marker set (27 static, 23 dynamic) to capture lower limb kinematics of 40 healthy female subjects during double leg jump landing (DL) and single-leg jump cutting (SC). Standard inverse dynamics were used to calculate the three-dimensional loads at the knee. **Results:** The 37 subjects with valid data were split into 2 groups (n=18) of high and low RTD. The High RTD group landed with significantly more knee flexion at initial contact (IC) during both the double leg and single leg jump cut tasks (p < 0.05). No significance was observed between RTD groups for peak anterior tibial shear force (pATSF) or peak knee extension moment pKEM (p > 0.05). **Conclusion:** Individuals exhibiting lesser knee extension RTD landed with lesser knee flexion at IC while performing both tasks. Landing with lesser knee flexion likely increases risk for ACL injury during ballistic movements. It may be beneficial to train athletes to increase knee extension RTD in order to promote greater knee flexion at initial contact during landing for the purpose of injury prevention.

Key Words: ACL, RTD, quadriceps, kinematics, kinetics

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The Influence of Knee Extension Rate of Torque Development on Sagittal Plane Knee Biomechanics during Landing

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

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Thank you,

Roy

CHAPTER 1

Introduction

Anterior cruciate ligament (ACL) injuries are relatively common among individuals engaging in sports requiring ballistic movements such as soccer or basketball (Loës, Dahlstedt, & Thomée, 2000; Lyman et al., 2009; Mather et al., 2013; Myklebust, Maehlum, Engebretsen, Strand, & Solheim, 1997). It is imperative to learn more about factors contributing to this injury in hopes of improving primary ACL injury prevention initiatives given that there are approximately 200,000 injuries per year in the United States alone with the average lifetime cost per injury estimated to be \$38,121-\$88,538 (Mather et al., 2013). Collectively, this places a great financial burden on society with estimated total annual costs between \$7.6-\$17.7 billion depending upon whether the initial ACL injury event is managed surgically or conservatively (Mather et al., 2013).

In addition to financial costs, ACL injuries also result in a significant reduction in patients' quality of life. Individuals that have sustained an ACL injury exhibit reduced physical activity levels and knee function, with a prolonged fear of movement even 20 years post injury (Tengman et al., 2014). In fact, fear of re-injury is a major contributor to the low rates of return to play observed in these athletes (Ardern, Webster, Taylor, & Feller, 2011; McCullough et al., 2012; Myklebust & Bahr, 2005). ACL injuries also contribute to a significantly increased risk of early onset osteoarthritis (Chaudhari, Briant, Bevill, Koo, & Andriacchi, 2008; Lohmander, Östenberg, Englund, & Roos, 2004; Porat, Roos, & Roos, 2004). A strong correlation between ACL ruptures and meniscal damage has also been established, which contributes to further increase the risk of osteoarthritis in this population (Dare & Rodeo, 2014; Potter et al., 2012).

A trend that has been well established in regards to those suffering ACL injury is that females are approximately 4-6 times more likely sprain their ACL than males participating in similar types of activities (Agel, Arendt, & Bershadsky, 2005; Arendt & Dick, 1995; Bjordal, Arnøy, Hannestad, & Strand, 1997; Loës et al., 2000; Myklebust, Mæhlum, Holm, & Bahr, 1998). Further, 70% of all ACL injuries occur without contact with another individual (Boden, Dean, Feagin, & Garrett, 2000) and specific movement patterns such as landing with lesser knee flexion have been identified as increasing an individual's risk for injury (Alentorn-Geli et al., 2009).

In regards to modifiable factors that are associated with ACL sprains, it is well-documented that loads on the ligament can be influenced by sagittal plane biomechanics. Most notably, a standardized isometric contraction of the quadriceps muscles while the knee is at or near full extension produces greater strain on the ACL compared to the same magnitude of quadriceps force at a more flexed knee position (Beynnon & Fleming, 1998; DeMorat, Weinhold, Blackburn, Chudik, & Garrett, 2004). The sagittal plane position of the knee influences ACL strain by altering both the patella tendon tibia shaft angle (PTTSA) and the ACL elevation angle. PTTSA is defined as the angle between the patella tendon and the longitudinal axis of the tibia (Yu & Garrett, 2007). Therefore, as knee flexion angle decreases, PTTSA is increased, while the anteriorly directed component of the quadriceps force increases (Yu & Garrett, 2007). ACL elevation angle is defined as the angle between the longitudinal axis of the ACL and the tibial plateau (Yu & Garrett, 2007). As knee

flexion angle decreases, the ACL elevation angle increases, which results in a more vertically oriented ACL, directing a greater proportion of the sagittal plane loading on the ligament from tensile to shear (Yu & Garrett, 2007). Though the quadriceps force responsible for sagittal plane ACL loading cannot be measured directly *in vivo* during landing, anterior tibial shear force (ATSF) and internal knee extension moment (KEM) are commonly used to infer quadriceps force during biomechanical studies. Therefore, when these factors are considered together, a straighter knee in combination with high quadriceps forces (i.e. ATSF and KEM) during landing likely results in increased ACL loading which increases ACL injury risk. In the literature, it has been noted that individuals landing with lesser knee flexion are at increased risk of ACL injury due to the combination of quadriceps loading that occurs as the knee is placed in an unfavorable position (Chappell, Yu, Kirkendall, & Garrett, 2002; Koga et al., 2010).

In a previous investigation examining the influence of sagittal plane knee position on knee biomechanics, it was reported that landing in a more flexed position was associated with lesser peak vertical and posterior ground reaction forces (GRF) (Podraza & White, 2010). As a result, more of the energy is thought to be absorbed by the musculature in the legs rather than in the bone and connective tissue (Podraza & White, 2010; Yeow, Lee, & Goh, 2009). However, landing in a more flexed knee position requires individuals to generate greater internal knee extensor moments to overcome an increasing distance between the knee joint center and the ground reaction force vector (Podraza & White, 2010). Therefore, it is possible that

individual's with lesser knee extensor strength might adopt a less flexed knee posture during landing in order to reduce the internal KEM demand.

In support of this notion, Chappell et al reported that following a fatigue protocol, males and females performed a stop-jump task with significantly lesser KEM and ATSF compared to before fatigue suggesting a potential modification in sagittal plane landing biomechanics to compensate for reduced quadriceps function. However, the knee flexion angle at initial contact was not reported in this study. Furthermore, Bennet et al did not identify a significant relationship between ATSF and peak quadriceps torque during a double leg landing task indicating that quadriceps strength may not influence sagittal plane knee biomechanics in a rested condition. However, one factor that is important to consider, but has not been taken into account previously, is the time interval in which the landing mechanics of interest occur (Bennett et al., 2008; Chappell et al., 2002; Lephart, Ferris, Riemann, Myers, & Fu, 2002; Moul, 1998; Myer et al., 2009; Slemenda et al., 1998).

While isometric torque is not achieved until approximately 250-300 ms after torque onset, peak KEM and ATSF generally occur around 50 ms after initial ground contact (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Koga et al., 2010). In explaining the importance of such a difference in timing, it is thought that individuals do not have sufficient time during landing to produce peak torque, so a measure of an individual's capacity to rapidly produce knee extension torque might be more relevant. One measure of explosive strength that is more relevant to the timing of peak knee kinetics during landing is the rate of torque development (RTD) (Aagaard et al., 2002). As the timing of peak sagittal plane knee kinetics coincides

with when ACL injuries are reported to occur (approximately 40-50 ms after IC) (Koga et al., 2010), the capacity to rapidly generate greater knee extensor torque over this time period might be important for using safer sagittal plane landing mechanics. Therefore, the purpose of this study was to evaluate the influence of knee extension RTD on sagittal plane knee biomechanics during two different types of landing tasks: double-leg jump landings and single-leg jump cuts. We hypothesized that females with greater knee extensor RTD would land with greater knee flexion angle at IC, lesser peak ATSF, and greater peak KEM during the two landing tasks.

CHAPTER 2

Literature Review

Incidence

Precise estimates within the field of exercise science of the frequency of ACL injury are relatively unknown. One study performed found that for high risk sport activities such as basketball, soccer, or ice hockey, ACL injury occurred once per every 100,000 hours of activity (Loës et al., 2000). Meanwhile, other studies have found there to be an overall average of 1% injury incidence to either the ACL or posterior cruciate ligament (PCL) for individuals performing similar high risk activities (Myklebust et al., 1997). Moreover, it has been established that ACL injuries are much more prevalent than PCL injuries (Lyman et al., 2009). With a rate of 200,000 reported injuries per year, anterior cruciate ligament injuries are a common injury in the United States (Mather et al., 2013). Even with this degree of variability between rates and ways of measuring incidence, the overall numbers suggest that there are a large number of people suffering this injury annually.

Cost

The average lifetime cost to society for a typical patient undergoing ACL reconstruction surgery is estimated to be \$38,121, and estimated to be \$88,538 for those who choose rehabilitation alone (Mather et al., 2013). From a societal perspective, the cost analysis took into consideration the effects of an ACL injury on one's work status, cost of treatment, and other factors other than the surgery itself (Mather et al., 2013). In the United States, these lifetime costs associated with ACL injuries are considerably high and are estimated to be \$7.6 billion annually if patients

were treated with ACL reconstruction, and \$17.7 billion dollars if treated with conservative rehabilitation measures alone (Mather et al., 2013). Due to the this financial burden to society, it is important to allocate resources to develop programs aimed at injury prevention (Mather et al., 2013).

Not only are ACL injuries expensive to society, they take a toll on other aspects of patients' lives following injury. Tengman et al. (2014) investigated the physical activity level, knee function, and fear of movement of individuals with an over 20 year past history of ACL injury. They found that, even after 20 years, those with a history of ACL injury choose activities that minimize load on the knee joint and have lower levels of physical activity, which might contribute to the higher BMIs that were observed for these individuals as compared to individuals who had never experienced an ACL injury (Tengman et al., 2014).

Another major issue associated with sustaining an ACL injury is the added likelihood that these individuals will develop early-onset osteoarthritis in the injured knee. Many studies have determined that even with an isolated injury to the ACL, and with reconstructive surgery, individuals are still more likely to develop osteoarthritis within the knee joint at an earlier age as compared to a healthy individual (Chaudhari et al., 2008; Lohmander et al., 2004; Porat et al., 2004). Contributing to yet higher rates of early osteoarthritis, it has also been found that ACL injuries are frequently accompanied by meniscal injury, which have been shown to increase the risk for osteoarthritis (OA) (Dare & Rodeo, 2014; Potter et al., 2012). This indicates that not only are ACL injuries costly from a financial perspective, but they are also costly in

the sense that they are limiting functionality of the joint much earlier than would be expected in healthy individuals.

With this loss of function and fear of the return to physical activity for individuals suffering this injury, comes issues related to capabilities of returning to play. One study found that following ACL injury and reconstruction, the percentages of amateur American football players returning to play are not "as high as would be expected" (Ardern et al., 2011). It was suggested that fear of re-injury played a crucial role in influencing the ability of these athletes to return to play at the level they were able to prior to their injury (Ardern et al., 2011; McCullough et al., 2012, 2012; Myklebust & Bahr, 2005).

Sex Differences in Risk of ACL injury

While males account for a greater absolute number of annual ACL injuries (Loës et al., 2000), it is well established that when compared to their male counterparts, females are 4-6 times more likely to sustain an ACL injury (Agel et al., 2005; Arendt & Dick, 1995; Bjordal et al., 1997; Loës et al., 2000; Myklebust et al., 1998). In regards to mechanisms of an ACL injury, it has been noted that approximately 70% of all ACL injuries occur without another individual directly contributing to some external force placed on the knee joint (Boden et al., 2000). Therefore, the way in which an individual moves likely influences their risk of an ACL injury. The most common movements associated with an ACL injury are rapid changes in direction and landing from jumps in near or full knee extension (Alentorn-Geli et al., 2009). Movement patterns that account for elevated rates of ACL injury in female athletes can be described by various biomechanical measures.

Sagittal Plane Biomechanical Factors

While forces in all three planes of movement can contribute to loading of the ACL (Markolf et al., 1995), the interest of this study is to investigate sagittal plane factors that can place strain on the ACL. Markolf et al. (1995) found that the most direct loading mechanism on this ligament was via straight anterior tibial translation. As the quadriceps muscles contract, they pull on the insertion point at the tibial tuberosity, which creates an anteriorly directed shear force on the tibia that places a load on the ACL. There have been cadaveric studies which suggest that when the knee joint is near full extension, an isometric contraction of the quadriceps can produce maximal strain on the ACL and even cause complete rupture of the ligament (DeMorat et al., 2004). Other studies have shown that when the knee joint is between 50 degrees of flexion and full extension, an isolated contraction of the quadriceps puts great strain on the ACL (Beynnon & Fleming, 1998).

Two biomechanical variables that are important to take into consideration in the sagittal plane are anterior tibial shear force (ATSF) and internal knee extension moment (KEM). ATSF is a resultant force that acts to move the tibia anteriorly with respect to the femur. As a result, a measurable strain can be placed on the ACL. When the magnitude of ATSF is increased, such as through increased quadriceps contraction, the ligament is placed under increasing strain and is more likely to rupture (DeMorat et al., 2004). A second biomechanical factor that is also known to be correlated with the magnitude of force placed on the ligament has to do with the rotational nature of the lower limb as the quadriceps muscle contract. In this case, the lower limb can be thought of as a lever which swings anteriorly as the knee is brought

to full extension. This variable is known as the internal knee extension moment (KEM) (Engel, Brueggemann, Heinrich, Potthast, & Liebau, 2015). Though not directly indicative of ACL strain, KEM is commonly used to infer the magnitude of quadriceps force during biomechanical studies as quadriceps force cannot be directly measured *in vivo*.

When looking at the structure of the knee joint, another factor influencing the magnitude of the ATSF produced via quadriceps contraction is the patella tendon tibia shaft angle (PTTSA). The PTTSA is defined as the angle formed between the line of pull of the patella tendon acting at the tibial tuberosity and the longitudinal axis of the tibia (Yu & Garrett, 2007). Therefore, as knee flexion angle decreases, PTTSA is increased and with a standardized amount of quadriceps force, the anteriorly directed component of the quadriceps force increases (Yu & Garrett, 2007). In addition to changing the PTTSA, reducing knee flexion angle also results in an increase in the ACL elevation angle. This angle is defined as the angle between the longitudinal axis of the ACL and the tibia plateau (Yu & Garrett, 2007). Mechanistically, a smaller knee flexion angle increases the ACL elevation angle which results in the ACL being oriented more vertically. In this position, less of the loading that occurs secondary to the ATSF is tensile and more is shear (Yu & Garrett, 2007). This is important to note because the ligament is structured anatomically in a way that is able to resist tensile forces much more adequately than shear forces. After exploring the variables mentioned above, it is established that athletes engaging in ballistic sports who consistently place forces on the knee while in a position of lesser knee flexion likely have an increased risk of an ACL rupture.

One study that applied these concepts by analyzing ACL injury video sequences from women's basketball and handball matches, consistently found that at the time of injury, the knee was relatively straight with a mean knee flexion angle of 23° (Koga et al., 2010). Chappel et al. (2002) found that as compared to males, female athletes tend to land with lesser knee flexion, which increased the proximal anterior shear force recorded. It was suggested that due to the observation that female athletes have altered motor control strategies, technical training should be implemented to reduce the peak anterior shear force during stop-jump tasks (Chappell et al., 2002). These factors are pertinent to the way in which force is transferred from the ground to the lower limbs during landing.

Knee Biomechanics in Landing

In terms of reaction forces, landing with a more flexed knee position as stressed above is known to result in lesser peak vertical and posterior ground reaction forces (GRF) (Podraza & White, 2010). This is attributed to the role antigravity muscles have in holding the person upright. When the knee is in a more flexed position, these muscles are in a more advantageous position to absorb the energy at impact with the ground, which has been thought to act to reduce the energy that is propagated up the lower limb kinetic chain (Podraza & White, 2010; Yeow et al., 2009). However, it is important to mention that utilizing a flexed knee position at initial contact during landing requires the ability to generate greater internal knee extension moment (Podraza & White, 2010). Podraza et al. reported that during a drop landing, peak knee extensor moment increased by 75% in conditions where the target knee flexion angle increased from 0-25 degrees to 25-50 degrees. This is due to the greater magnitude of the distance the resultant GRF vector has in relationship to the knee joint axis (Hamill & Knutzen, 2006; Podraza & White, 2010). In regards to peak knee extension moment and landing, it is also important to mention the timing at which this occurs and relationship between quadriceps strength with sagittal plane biomechanics.

Quadriceps Strength and Sagittal Plane Landing Biomechanics

The literature suggests that, in general, there is a significant difference between males and females in regards to the ability to generate peak torque (Arendt & Dick, 1995; Lephart et al., 2002; Moul, 1998; Slemenda et al., 1998). One study done that clearly delineates this difference evaluated kinematic, GRF, and strength variables in collegiate level female athletes who participate in ballistic sports including basketball, volleyball, and soccer. The values were compared with matched male participants. Maximum angular displacement was calculated for a variety of kinematic variables including knee flexion. To measure peak torque, a Biodex System III (Biodex Medical Inc, Shirley, NY) dynamometer was used and was normalized against body mass. As predicted, it was found that females had significantly less peak torque normalized to body mass, less knee flexion displacement, and less time to maximum knee flexion compared to males (Lephart et al., 2002). The conclusion was that there is a relationship between weak thigh musculature and "stiffening" of the lower leg and knee joint during landing in females, which may place the knee in a compromised state.

Even after using peak torque as a strength measure to describe the correlation between weaker quadriceps in females and lesser knee flexion during initial contact

with the ground, there is one disjunction in the explanation that is yet to be adequately addressed in the literature. Results are inconsistent when it comes to explaining sagittal plane biomechanics with peak KEM alone (Bennett et al., 2008; Myer et al., 2009). One potential reason for this is that peak torque takes approximately 250-300 ms to develop (Aagaard et al., 2002), while peak KEM occurs much earlier at around 50 ms. For this reason, a measure of strength that incorporates a rate driven component might be more applicable when evaluating sagittal plane knee biomechanics.

Rate of Force Development and Muscular Strength

Strength can be an important indicator of the types of movements a person is likely to perform during a given activity. There are different ways strength can be quantified. Due to the relative short timing in which most injuries occur, one approach focuses on evaluating "explosive" muscular strength (Aagaard et al., 2002). A method gaining popularity in the field of exercise science evaluates the rate at which contractile force increases. The term recognized with the use of this method is called rate of force development (RFD). With the pivoting nature of some joints such as the knee, a similar term used in the literature is referred to as rate of torque development (RTD). This measure of "explosive" strength is therefore found by taking the slope of a torque-time curve. The importance of such a measure is that it is applicable to the types of ballistic sports that put individuals at higher risk of ACL injury (Aagaard et al., 2002). These sports, which may include running, basketball, and soccer, involve contractile times during landing that are quite rapid (50-250 ms) (Koga et al., 2010). It is during these landings when most injuries occur (Koga et al.,

2010). In contrast, it may take longer (greater than 300 ms) for peak force to develop within a muscle (Aagaard et al., 2002). Due to the time during which ACL ruptures are reported to occur (around 40 ms) (Koga et al., 2010), it is very important to investigate RTD, as explosive knee extensor strength may be more influential to sagittal plane knee biomechanics than peak knee extensor strength.

Conclusion

From this literature review, there are several key conclusions to be noted. There is a large body of literature which supports the notion that ACL injuries are common among active individuals. ACL injuries not only have a tremendous financial cost to individuals, but they also place a large financial burden on society. Furthermore, not only are these injuries costly from a financial perspective, but they are also costly in the sense that they are limiting functionality of the joint much earlier than would be expected in healthy individuals by causing early onset osteoarthritis. Issues with returning to play after sustaining such an injury also arise.

It has been established that athletes engaging in ballistic sports who consistently place forces on the knee while in a position of lesser knee flexion likely have an increased risk of an ACL rupture as the strain on the ACL due to these forces is increased secondary to changes in the PTTSA and ACL elevation angle. Markedly, it has been consistently shown that females are at greater risk for ACL injury than males. In explaining which movement patterns are placing female athletes at risk for ACL injury, females tend to land with lesser knee flexion. One potential reason for the use of less flexed knee positions is that females have been shown to have significantly lesser knee extensor strength than males. Furthermore, landing with

greater knee flexion has been shown to require greater knee extension moment. As a result, females might adopt a more extended knee position during landing to compensate for lesser knee extensor strength.

Finally, the manner in which strength is assessed is important. Given the relative short timing in which peak KEM is observed to occur, an explosive measure of strength (RTD) may be more useful in explaining the relationship between knee extension strength and sagittal plane knee biomechanics than peak torque. As a result, the purpose of this study was to investigate the influence of knee extension RTD on sagittal plane knee biomechanics during landing.

CHAPTER 3

Methods

Subjects

Forty female volunteers (age = 21.0 ± 1.7 years; height = 67.4 cm ± 7.81 cm; mass 65.89 kg \pm 8.54 kg) from the Oregon State University population were included in this study. In compliance with Institutional Review Board (IRB) policies and regulations, subjects were recruited through announcements in classes, informational flyers, and word of mouth. To be eligible for inclusion in the study, participants reported 1) no current injuries or illnesses that limit their ability to perform their regular physical activity, 2) no lower extremity or low back injuries in the previous six months that limited their regular physical activity, 3) no history of low back, hip, knee, or ankle surgery, 4) no history of ACL injury, 5) completing on average at least 150 minutes of moderate to vigorous physical activity a week, and 6) participating in a form of physical activity involving cutting or jumping within the previous six months. All subjects read, signed, and demonstrated that they understood the IRBapproved informed consent form which described both the procedures and the risks associated with participation in the study. Following informed consent, subject height and mass were measured.

Subject Preparation and Experimental Procedures

Before the start of the testing session, subjects warmed up at their own pace on a stationary bicycle for 5 minutes. Strength testing of the knee joint for the purpose of recording RTD values was done by positioning the participants on a dynamometer, and instructing them to perform an isometric knee extension contraction. The

dynamometer arm had a padded attachment arm that the individuals pushed against during the testing. In order to measure knee extension, the subjects were positioned in the seated dynamometer bench with their dominant knee flexed at approximately 70 degrees. Participants' leg dominance was determined by the leg they used for the majority of these three tests: 1) kicking a ball, 2) stepping up onto a step, and 3) recovering from a small perturbation from behind (Hoffman, Schrader, Applegate, & Koceja, 1998). The dynamometer was aligned with the lateral epicondyle of the dominant leg. The attachment was secured just above the subject's ankle. The subject was asked to push as "hard and fast" as they could against the dynamometer once they saw a light stimulus in order to perform an isometric contraction of their quadriceps muscles. A minimum of 3 trials were collected. Each trial lasted no longer than 5 seconds and was followed by 1 minute of rest. A maximum of 3 practice trials and 5 testing trials were collected.

Following assessment of quadriceps RTD, subjects were movement fitted bilaterally with 27 retroreflective markers placed bilaterally on the acromion process, anterior superior iliac spine, posterior superior iliac spine, greater trochanter, anterior thigh, medial and lateral femoral epicondyles, anterior tibial shaft, medial and lateral malleoli, and approximate locations of the calcaneus, 1st and 5th metatarsal heads. A marker was also affixed to the L5-S1 joint space. A nine camera motion capture system (Vicon, Inc., Centennial, CO, USA) was used to record subject kinematics during a static calibration trial, double leg jump landings, and single leg jump-cuts.

Double leg jump landings included the use of 2 force plates (Type 4060-08, Bertec Corporation, Columbus, OH, USA) as subjects stood on top of a 30 cm high

box which was placed at a distance measuring 50% of their height. The subjects were instructed to jump down from the box landing one foot in the center of each force plate, and immediately jump up for a maximum height while using a continuous motion. For the single leg jump-cut task, subjects begin at a distance that was 50% of their height away from the edge of the force plate with both feet parallel and in contact with the ground. Subjects were then instructed to jump over a box measuring 17 cm located 25% of their height away from the edge of the force plate with their dominant foot only and perform a 45 degree cut towards the direction of the non-dominant limb. Participants were instructed to perform the jump-cut task as quickly as possible.

Before recording of the testing trials, participants demonstrated proper form on a minimum of 3 practice trials for each of the tasks. To reduce the potential effects of fatigue, subjects were given 30 seconds of rest between each of the five successful testing trials for each task. A successful double leg jump task was characterized by the subject landing with both feet fully within the bounds of each force plate at approximately the same time, and performing this task in a fluid motion. A successful single leg jump cut was characterized by the subject landing with the dominant foot fully on the force plate and accelerating out of the planted position at a 45 degree angle away from the plates in a fluid motion.

Data Sampling, Processing, and Reduction

The raw voltage signal from the Biodex System 3 dynamometer was sampled at 1560 Hz using The MotionMonitor software during each of the knee extension RTD trials. The recorded voltage signal for each trial was digitally low-pass filtered

at 10 Hz using a fourth-order Butterworth filter and converted to torque (N·m) via a calibration equation function using custom computer software (LabVIEW, National Instruments Corp., Austin, Texas). This same custom software was used to calculate knee extension RTD during the 50 ms immediately after the torque onset (i.e., time point when torque exceeded 2.5% of peak torque). RTD was calculated as the slope of the line that best fit the torque-time curve over the period of interest (0-50 ms). The maximum RTD value calculated during any of the trials was used and normalized to the product of body height and weight for statistical analysis.

Vicon Workstation motion capture software (Vicon, Inc., Centennial, CO, USA) was used to record kinematics and force plate measures at a sampling rate of 120 Hz and 1560 Hz, respectively. Raw, three dimensional kinematic coordinates and force plate data were imported into the MotionMonitor motion analysis software (Innovative Sports Training, Chicago, IL, USA). The software was then used for biomechanical modeling. Midpoints between the medial and lateral malleoli and medial and lateral epicondyles were used to define ankle and knee joint centers, respectively. External landmarks were used to predict the hip joint center. Local, segmental coordinate axis systems were defined for the sacrum, thigh, shank, and foot (Bell, Brand, & Pedersen, 1989). The positive x-axis was defined as being directed anteriorly, the positive y-axis pointing leftward, and the positive z-axis pointing superiorly. Kinematic and force plate data were low pass filtered at 10 Hz using a 4th order zero-phase lag Butterworth digital filter. Kinematic data was time synchronized to kinetic data and resampled at 1560 Hz. Knee motion was defined as the shank relative to the thigh. Joint angular positions were calculated using Euler angles in a Y

(flexion/extension), X' (abduction/adduction), and Z'' (internal/external rotation) rotation sequence using a right hand convention. The MotionMonitor was used to calculate internal intersegmental knee forces and moments of force using an inverse dynamics approach as described by (Gagnon & Gagnon, 1992). Custom computer software (LabVIEW, Inc., Austin, TX, USA) was used to identify dominant limb knee flexion angle at initial contact (IC), as well as peak KEM and ATSF during the 100 ms immediately after IC (defined as the time when VGRF > 10N). Mean values for each dependent variable were calculated for the 5 trials for each task. The participants' body weight was used to normalize ATSF, while KEM was normalized to the product of the subjects' height and weight.

Statistical Analysis

Subjects were separated into 2 groups (high RTD and low RTD) based upon their normalized knee extension RTD. The mean values for each DV during each task were compared using separate, one-tailed, independent samples *t*-tests. Statistical significance was set *a priori* at $p \le 0.05$.

CHAPTER 4

Results

Out of the 40 subjects recruited for the study, 3 were not used for the purpose of data analysis due to invalid double leg jumping biomechanical data. The 37 remaining subjects were ranked based on knee extension RTD and High and Low RTD groups were created by including participants with the 18 highest and 18 lowest RTD scores, respectively (using one subject from the 37 as the separation point for the groups). As expected, the High RTD group demonstrated significantly greater knee extension RTD than the Low RTD group (p < 0.001, Figure 1). With respect to sagittal plane knee biomechanics, the High RTD group landed with significantly more knee flexion at initial contact during both the double leg (p = 0.044) and single leg jump-cut (p = 0.045) tasks (Figure 2). However, no significant differences were observed between groups for peak ATSF during the double leg (p = 0.432) or the single leg tasks (p = 0.446); or for peak KEM during the double leg (p = 0.482) or





Figure 2. Knee Flexion Angle at Initial Contact. The High RTD was positioned in significantly less knee flexion at initial contact during both the double-leg landing (DL) and single-leg jump-cut (SC) tasks than the Low RTD group (p < 0.05).



Figure 3. Peak Internal Knee Extension Moment. No significant differences between RTD groups were identified during either the double-leg landing (DL) or single-leg jump-cut (SC) (p > 0.05).



Figure 4. Peak Anterior Tibial Shear Force. No significant differences between RTD groups were identified during either the double-leg landing (DL) or single-leg jump-cut (SC) (p > 0.05).



CHAPTER 5

Discussion

The primary finding of this investigation is that females with greater explosive knee extensor strength land using greater knee flexion at initial contact during both a double leg jump landing and a single leg jump-cut. However, knee extensor RTD did not influence the magnitude of peak KEM or ATSF during either landing task.

It has been well established in the literature that landing with lesser knee flexion at initial contact with the ground can be detrimental to the integrity of the knee joint (Lephart et al., 2002; Podraza & White, 2010). Two sagittal plane factors pertinent to influencing the magnitude of ACL loading during landing include the patella tendon tibia shaft angle (PTTSA) and the ACL elevation angle, both of which are affected by the sagittal plane position of the knee. The PTTSA is defined as the angle between the patella tendon and the longitudinal axis of the tibia (Yu & Garrett, 2007). As knee flexion angle decreases, PTTSA is increased and with a given contraction of the quadriceps, the magnitude of the anteriorly directed component of the quadriceps force is increased (Yu & Garrett, 2007). In addition, reducing knee flexion angle also results in an increase in the ACL elevation angle, defined as the angle between the longitudinal axis of the ACL and the tibia plateau, which results in a more vertical orientation of the ACL and increases the proportion of ACL loading that is shear relative to tensile (Yu & Garrett, 2007). This is dangerous to the stability of the ACL because of the vulnerability of ligaments to shear forces as compared with tensile forces. Consistent with our hypothesis, those with lesser knee extensor RTD consistently landed with less knee flexion at initial contact across two different types

of landing tasks (double-leg jump landing and single leg jump-cut). However, significant differences between groups were not observed for the kinetic variables (pKEM and pATSF) during either landing task. Therefore, although females with lesser knee extensor RTD exhibited similar peak ATSF and KEM as those with greater RTD, they did so with the knee positioned in lesser knee flexion, which is likely more dangerous given the expected corresponding increases in PTTSA and ACL elevation that could result in greater ACL strain.

Though unexpected, the lack of group differences in peak kinetics during the double leg jump landing and single leg jump-cut tasks may have been related to the limited magnitude of the difference in knee flexion angle at initial contact between groups. Podraza & White (2010) reported a 75% increase in peak KEM when experimentally controlling landing such that the mean difference in initial contact knee flexion angle between conditions was approximately 17 degrees. In contrast, the difference in knee flexion angle at initial contact between High and Low RTD groups during double leg landings and jump-cuts were 3.5 and 4 degrees, respectively. In regards to ATSF, other studies have failed to show a significant change in this measure while performing similar jumping tasks (Bennett et al., 2008). A potential explanation for these results is that perhaps the two tasks were not difficult enough on the musculoskeletal system to produce a large enough difference in knee flexion angle between groups to result in the greater and lesser ATSF and KEM, respectively, that was expected. It is possible that as the biomechanical demands on the knee increase during the performance of real-world sporting activities, the difference in

knee flexion angle would also correspondingly increase and lead to differences in sagittal plane knee kinetics. However, future testing is needed to evaluate this notion.

With ACL injury prevention in mind, the results of this study support the notion that it may be beneficial to specifically train knee extensor RTD in an effort to facilitate a more flexed knee position at initial contact. A range of studies have demonstrated that training programs can significantly improve RFD/RTD. A 14-week long lower body training program involved the use of a variety of exercises. These included hack squats, incline leg press, isolated knee extension, hamstring curls, and seated calf raises which would target the major muscle groups of the legs including the gluteal, quadriceps, hamstrings, and gastrocnemius/soleus. The results showed greater RFD across all time intervals of 0–30, 0–50, 0–100, and 0–200 ms, as well as peak RFD following training (Aagaard et al., 2002). Another study focused on the barbell deadlift as the primary method of exercise. This study found an increase in peak RFD at 50 and 200 ms after 10 weeks of training (Thompson et al., 2015).

Heggelund et al (2013) investigated the effect of maximal strength training as compared to equal volume of conventional strength training on RFD during single leg knee extension. The study involved 8 untrained or moderately trained men who underwent training in an intra-individual design, where one leg was randomized to knee extension maximal strength training (MST) and the other was subjected to conventional strength training (CON). This meant that one group lifted three sets of 10 repetitions at 60-70% maximum weight, while the other group lifted only 4-5 repetitions at 85-95% of maximum weight three times per week for 8 weeks. It was concluded that 8 weeks of MST was more effective than CON for improving RFD in

untrained and moderately trained men (Heggelund, Fimland, Helgerud, & Hoff, 2013).

In addition to frequency and load, one training related factor that may be important to consider when attempting to specifically increase knee extensor RTD is to incorporate "an intention to move quickly" (Young & Bilby, 1993). A study split two groups of healthy males into two categories and tested the influence of one's cognitive state on measurable explosive strength values. Both groups underwent a 7.5 week resistance training program with half-squat exercises. The first category of men was told to produce "fast concentric contractions," while the other group emphasized "slow controlled movements." Following training, static strength was significantly improved for the slow group, while RFD increased significantly for the fast group. The results suggest that training programs designed to improve RFD/RTD should include a focus on intending to produce fast movements while training (Young & Bilby, 1993).

Regardless of the type of training utilized, the results of the present investigation suggest that improving explosive knee extensor muscle strength may encourage the use of more knee flexion across different types of landing tasks. As the use of lesser knee flexion during landing is associated with an increased risk of ACL injury, the implementation of training programs specifically focused on the development of rapid knee extension torque might be useful as a means to increase the knee flexion of females during a variety of landing tasks.

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