BIOMECHANICAL RISK FACTORS ASSOCIATED WITH NON-CONTACT ANTERIOR CRUCIATE LIGAMENT INJURIES DURING LANDING PERFORMANCE

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Anterior cruciate ligament (ACL) injuries have received much attention in the biomechanics literature. The kinematics and kinetics of landing appear to be important risk factors for non contact ACL injuries especially for females. This paper reviews many of the some of the biomechanical factors that appear to be important to ACL injury risk and how recent modeling approaches have been utilized. Modeling studies depict a rather complex interaction of kinematic, kinetic and anatomical factors that result in ACL loading early in landing. More complex, subject and gender specific models may be important to gain further insight and thus influence injury prevention efforts.

KEY WORDS: Knee, injury, biomechanics.

Annually, an estimated 80,000 to 250,000 anterior cruciate ligament (ACL) injuries occur in the US alone (Griffin et al., 2006). ACL rupture is commonly treated with surgical intervention for reconstruction and pre-operative and post-operative rehabilitation. In 2011, the average national cost of an ACL reconstruction surgery was $12,740 (Lubowitz and Appleby, 2011). Additional costs include evaluation, imaging, and the use of physical therapy. Those who have sustained an ACL rupture are 3 times more likely to develop osteoarthritis as compared to the national average, regardless of the treatment approach (Ekegren et al., 2009) Non-contact anterior cruciate ligament (ACL) ruptures often occur in athletes during movements that involve significant decelerations such as landing from a jump or in cutting (Boden et al., 2000; McNair et al., 1990; Olsen et al., 2004)) The anterior cruciate ligament is a intracapsular ligament attaching to the posterior part of the medial surface of the lateral condyle posterior to the longitudinal axis of the femoral shaft to the fossa in front of and lateral to the anterior spine of the tibia (Amis & Dawkins, 1991). Due to the ACL's anterior posterior orientation, it provides restriction to anterior translation of the tibia on the femur.

Biomechanical performance differences between males and females during cutting and landing maneuvers have been identified as biomechanical risk factors that can be reliably measured in laboratory settings (Chappell et al., 2002; Decker et al., 2003; Ford et al., 2003; Hewett et al., 1999; Hewett et al., 2005a; Kernozek et al., 2005, Kernozek et al., 2008, Lephart et al., 2002; Yu et al., 2005; Yu et al., 2006). Healthy females tend to land with reduced knee flexion angles compared to males (Chappell et al., 2002; Decker et al., 2003; Kernozek et al., 2005; Lephart et al., 2002; Salci et al., 2004; Schmitz et al., 2007) where noncontact ACL injuries are purported to be more common (Boden et al., 2000; Cerulli et al., 2003). Landing with a reduced knee flexion may produce large anterior shear forces across the knee as the quadriceps contract and consequently results in high levels of ACL strain (Markolf et al., 1995). Landing with greater flexion knee may modulate the anterior shear force, Cabaud (1983) reported that knee flexion of 30° is thought to produce minimal strain on the ACL.

Gender differences in lower extremity frontal plane kinematics and kinetics have also been described during landing tasks (Ford et al., 2003; Kernozek et al., 2005; Russell et al., 2006). Females tend to exhibit larger knee abduction moments and larger peak knee abduction angles compared to males when landing (Ford et al., 2003; Kernozek et al., 2008a, 2005). A widely cited prospective study of 205 adolescent female athletes, Hewett et al., 2005b reported that females who later sustained an ACL injury (n = 9) had larger peak knee abduction angles, greater internal knee abduction moments, as well as higher ground reaction forces and shorter stance times during a drop jump landing task compared with the uninjured participants. Knee abduction moment during the impact phase of the jump-landing had a sensitivity of 78% and a specificity of 73% for predicting ACL injury status over the 13 month observation period.

Temporal differences in frontal plane knee motion during landing have also been reported. Peak knee abduction and hip adduction occurred earlier in females than in males during a drop-jump landing (Joseph et al., 2011). Correspondingly, knee abduction angular velocity was nearly two-times greater in the female subjects. In females, maximum hip adduction and knee abduction occurred before maximum knee flexion (i.e. during the deceleration phase) but after maximum knee flexion in males (i.e. during the acceleration phase). These suggest that females tend to collapse more rapidly into knee abduction and achieve larger peak knee abduction angles than males.

Lower extremity strength (Hewett et al., 2008; Lawrence et al., 2008), activation (Zazulak et al., 2005) and laxity (Shultz & Schmitz, 2009) have been implicated to risky knee positions during landing. Reduced hip external rotation strength appears to result in greater knee frontal plane moments in landing (Lawrence et al., 2008). Delayed gluteus maximus activation coupled with higher rectus femoris activation has been reported in females (Zazulak et al., 2005). Females with greater knee laxity in the frontal plane (adduction-abduction) and transverse plane (internal-external rotation) landed in greater knee abduction and hip adduction during drop jump landing (Shultz & Schmitz, 2009). This may place greater demands on the neuromuscular system to stabilize the knee joint during landing.

Modeling and Simulations of Landing Performance
Kernozek & Ragan (2008), Southard et al. (2012) and Kulas et al., (2010) have used motion capture and inverse dynamics data from landing to estimate either ACL tension or tibiofemoral shear forces. These models use cadaveric data as the basis for several modeling parameters. Using 2 dimensional knee models, each have estimated peak loads on the ACL occurs very early in the landing (less than 50 ms) (Figure 1A & B). This appears largely influenced by the posterior slope of the tibia (Kernozek & Ragan, 2008). These authors suggest that landing with more knee flexion may modulate the anterior shear force.

A) B)

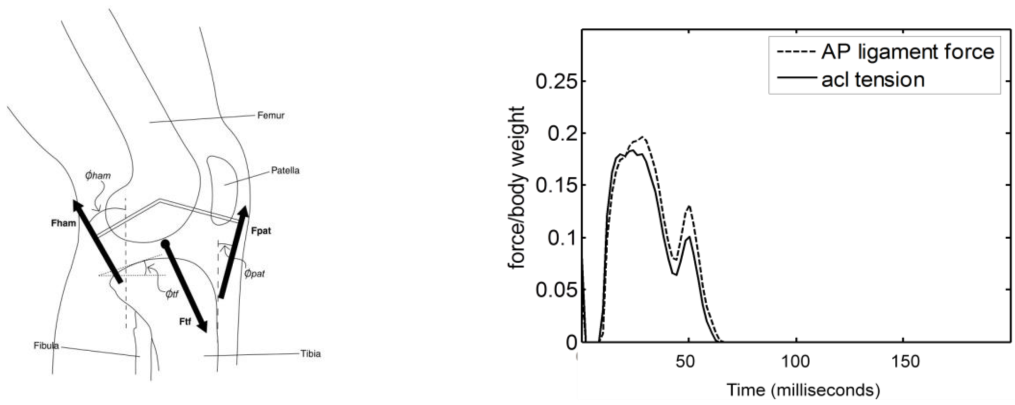

Figure 1. A) Two dimensional model of knee as described in Kernozek & Ragan (2008). B) estimated anterior/posterior ligament force and ACL tension for landing.

Southard et al., 2012 reported that less knee flexion reduced the ability of the hamstrings to provide a posterior shear force due to a less perpendicular angle of pull relative to the tibia while increasing the anterior shear force from the quadriceps due to a less vertical angle of pull of the patellar tendon (Figure 2 a & b). Similar findings were shown with muscle model simulations of soft and stiff landings. Laughlin et al. (2011) reported high ACL loads early within the landing that could be reduced by decreasing landing stiffness and altering knee angle at impact. Using more sophisticated computational modeling and simulation techniques, Pflum et al. (2004) calculated the estimated force transmitted to the ACL during a soft-style drop-landing to explain the pattern of force transmission. In all of these investigations, it appears that ACL load decreased to zero shortly after initial impact and then increases quickly to reach a maximum (~ 0.25-0.4 BW).

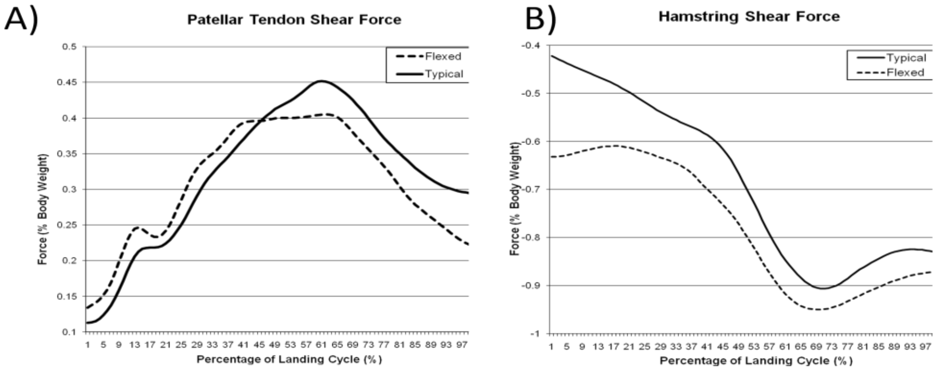

Figure 2 A) Peak patellar tendon shear force during a typical and flexed landing strategy. B) Peak hamstring shear force during a typical and flexed landing strategy.

Lack of subject specific models may be important to estimated ACL loads. Kernozek et al. (2012) systematically varied some model parameters and showed that anatomical variation of tibial slope and patellar tendon parameters were most influential in estimated ACL loading during drop landing. ACL tension estimates were less sensitive to hamstring attachment points and lines of pull. All current modeling studies have not used subject or gender specific data. Many have utilized a tibial slope of 8º. Imaging studies by Hashemi et al. (2008, 2010) indicated anterior/posterior tibial slope may be important to ACL injury. In fact the difference in medial/lateral slope appears particularly relevant. Further studies indicating the presence of gender differences in these model parameters seems warranted.

One commonly held belief is that landing with an extended knee increases the anterior pull of the quadriceps, which in turn strains the ACL. Pflum et al., (2004), in agreement with others (Domire et al., 2011; McLean et al., 2004) indicated that the pattern of ACL force in landing cannot be explained by quadriceps force alone. The maximum force transmitted to the model ACL appear to result from a complex interaction between the patellar tendon force, the compressive force acting at the tibiofemoral joint through the tibial slope, and the force applied by the ground to the lower leg (Hashemi et al., 2011; Pflum et al., 2004, Kernozek & Ragan, 2008). While the role of the patellar tendon appears important in determining peak ACL loading in landing, the other contributions to the shear forces at the knee seem just as important and cannot be discounted.

With the evolution of biomechanics and musculoskeletal modeling, great gains in understanding factors linked to tissue loads have been made. However, one must use some caution with interpreting data from marker based capture due to the skin artifact. In addition, lack of standardization with the signal filtering processing, force and marker based movement data may lead to differences in knee moment measurements during high impact activities (Kristianslund et al., 2012).

In summary, human performance studies have shown considerable performance differences in landing between genders. Modeling efforts have largely not explored gender issues and have been mostly limited to 2D. Future investigations utilizing more sophisticated, subject specific, three dimensional models of the knee coupled with fluoroscopic measures (Torry et al., 2011, 2013) may lead to further insights on how many of these parameters discussed may interact during dynamic loading scenarios. Prevention programs will continually need to adapt to these new insights of potential ACL injury mechanisms of female athletes.

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