Neuromuscular contributions to anterior cruciate ligament injuries in females

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Although anterior cruciate ligament (ACL) injuries are not gender specific, they do occur at a significantly greater rate in females. Biomechanical and neuromuscular deficits in females have been documented as factors contributing to ACL injuries, however little research has been conducted in the area of preventative training programs to improve these deficits. This article will describe the biomechanical and neuromuscular factors that contribute to ACL injuries in females, and provide a foundation from which preventative training programs should be designed. Curr Opin Rheumatol 2002, 14:168–173 © 2002 Lippincott Williams & Wilkins, Inc.

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Abbreviations

ACL	anterior cruciate ligament
EMD	electromechanical delay
GTO	golgi tendon organ

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Anterior cruciate ligament (ACL) injury rate in the United States exceeds 1 in every 3,000 persons. Of these physically active individuals, females tear their ACL two to eight times more frequently than their male counterparts with the risk of injury increasing with participation in the sports of soccer and basketball [1–6]. A 1999 National Institutes of Health/American Academy of Orthopaetic Surgeons-sponsored consensus conference on female ACL injuries determined that biomechanical and neuromuscular factors are the most likely risk factors associated with this injury. Current research has shown that the most vulnerable moment related to the injury is ground contact while landing, coupled with an awkward body position. A series of studies over 4 four years suggests that intercollegiate female athletes have significantly different proprioceptive characteristics [7,8], muscle firing patterns [9,10], and landing strategies [11] compared with their male counterparts, and that there may be several underlying physiological mechanisms potentially responsible for these differences [7–11].

Anatomy and biomechanics

The knee is classified as a modified hinge joint; in fact, it is the largest and most complex in the body. This tibiofemoral joint allows flexion and extension in the sagittal plane by rolling, spinning, and gliding [12]. The tibial plateau and asymmetrical condyles provide limited boney structural support while the soft tissue structures are largely responsible for providing static and dynamic support to the joint.

The soft tissue structures that provide static support to the knee are the capsule, the ligaments, and the meniscus, which are also referred to as primary stabilizers or restraints [12]. These primary restraints are mechanical in nature and are responsible for stabilizing and guiding the skeletal components [12]. The anterior cruciate ligament (ACL) is responsible for resisting anterior translation of the tibia onto the femur, specifically resisting 80–85% of anterior transitory loads [12,13]. The ACL is made of two bundles, the anteromedial and posterolateral. Both bundles rise from the posterior medial femoral condyle and insert into the anterior medial aspect of the tibial plateau [12]. Anterior instability or translation is the result of ACL rupture; therefore, the muscles and tendons must compensate for the increased joint motion to maintain joint stability [14].

The soft tissues that provide dynamic support to the knee are the tendons and muscles, which are referred to as secondary stabilizers or restraints. The quadriceps, hamstrings, and gastrocnemius are the main secondary stabilizers of the knee. The orientation of the proximal attachments of the gastrocnemius and the distal attachments of the hamstrings are important to the dynamic stabilization of the knee because they provide a posterior force on the tibia that counteracts anterior translation. Specifically, the hamstring muscle group is synergistic to the ACL by unloading the ligament via increasing the load to failure rate, up to 40% [12,15,16]. Previous research suggests that several neuromuscular characteristics contribute to this dynamic restraint mechanism [16–19].

Dynamic restraint mechanism

Embedded within capsuloligamentous and tenomuscular structures are mechanoreceptors that send neurosignals about tissue deformation [20,21]. As tissue deformation increases, the frequency of neurosignals and the number of mechanoreceptors that are stimulated are also increased. There are three main types of mechanoreceptors found in the knee. Pacinian corpusles, located in the joint capsule, which quickly depolarize subsequent to a stimulus and provide conscious and unconscious sensation of joint motion (kinesthesia) [21,22]; Meissner corpulses or Ruffini endings, housed within ligaments, menisci, and capsular tissue, which slowly adapt to stimuli and provide constant feedback concerning joint position (proprioception) [21,22]; and Golgi tendon orgranlike endings, located in the ligaments and menisci, which are also slow to adapt, and are thought to detect extreme ranges of motion [21]. The mechanoreceptors in the ACL are believed to contribute to the dynamic restraint system only when it is overloaded [15].

Mechanoreceptors located within skeletal muscle are called muscle spindles. Muscle spindles sense changes in muscle length and velocity [23]. They mediate muscle activity via stretch reflexes, which transmit afferent signals to motor nerves through monosynaptic pathways [23]. Additionally, mechanoreceptors located near the musculotendinous junction are called golgi tendon organs (GTO's) and monitor muscle tension [23]. Golgi tendon organs reflexively activate antagonist muscles and inhibit agonist muscles thus causing reflex inhibition or relaxation [23].

Information gathered from these mechanoreceptors was thought to be transmitted from the peripheral receptors through the afferent pathways to the central nervous system [24]. A direct reflex loop is formed between the afferent structures and the efferent motor nerves. For example, anterior translation loads cause an excitatory response on the hamstrings and gastrocnemius muscles [25,26] and an inhibitory response on the quadriceps [27]. These reflexive muscular contractions are theorized to contribute to dynamic stability [15]. Conversely, alternative theories state that afferent information from ligaments does not directly affect the motor nerves as once proposed. Instead, afferent information affects the muscle spindles, which regulate muscle activity via the stretch reflex's feedback loop that constantly modifies muscle activity [18,27,28]. For example, a 5 N force on the ACL excites the muscle spindles of the hamstrings [27].

Neuromuscular characteristics of dynamic restraint

Several characteristics contribute to the dynamic restraint system, which allows joint stability in potentially unsafe conditions. Neuromuscular control involves information from the proprioceptive, kinesthetic, visual, and vestibular systems, and also involves cortical and spinal motor commands [20]. Only a few aspects of neuromuscular control will be focused on in this section.

Preparatory and reactive muscle activity

Recent scientific theories focus on preactivated muscle patterns that anticipate movement and joint loads [29]. These muscle patterns are acquired by performing a task, whereupon sensory information is fed forward to preprogram muscle activity for future tasks. This is described as feed-forward neuromuscular control. This mechanism is important to dynamic stability because it provides fast compensation for encountered external loads [29–34]. Preparatory muscle activity is derived from centrally generated motor commands and high-speed movements that create a model of the parameters of a task [27,33]. When executing motor commands very quickly, the feed-forward mechanism is not dependent on reflex pathways, but instead increases the sensitivity of the muscle spindles, which in turn increase the awareness of joint motion and position [27,28,30]. Thus, sensory information is used to assess the results of a task, adjust accordingly for future motor patterns, and influence reactive muscle activity.

Muscle activity that occurs after a perturbation or event is termed reactive muscle activity. Sensory information is constantly fed back through several reflex pathways to coordinate muscle activity to complete a task [33]. To effectively coordinate muscle activity to protect a joint, the reactive activity requires a very fast response; 30–70 ms [17,25]. Unfortunately there is a latency period between preparatory and reactive muscle activation that is a result of electromechanical delay (EMD). Men were found to have a shorter EMD than women [34,35]. It is likely that preparatory muscle activity improves reactive muscle activity via the muscle spindles by identifying unexpected perturbations more quickly [17,25,29,30]. However, the amount of time taken to generate reactive muscle activity and the production of adequate force will determine the efficiency of dynamic stabilization [17].

Muscle force production

Muscle force production is one of several neuromuscular characteristics that assist muscles in providing dynamic stability. If the muscle cannot generate a sufficient amount of force in a timely fashion, excessive joint motion may occur, and ultimately, this may affect static structures [15,17,31]. Males are typically stronger than females; most likely a result of differences in muscle mass and possibly elastic tissue composition. The shorter EMD times of males may also contribute to the strength difference between the genders. Additionally, fatigue was linked to slower leg muscle response to perturbation and increased anterior tibial translation, possibly resulting in decreased dynamic stability of the knee [36].

Specifically, qualitative measures of the time required to attain the peak torque of muscle force are most often determined by isokinetic evaluation. The variable used to assess strength is peak torque, or peak torque to body weight ratio, which normalizes the data to make comparisons among subjects. Men and women possess strength differences of the quadriceps and hamstrings; in particular, women have a lesser amount of hamstring strength [37]. As the speed of the isokinetic test increases, the corresponding hamstring strength decreases and the knee angle at which peak torque occurs is later in the range of motion [37,38]. Additionally, females generate hamstring peak torque significantly later in the range of motion for 60° and 180°/second compared with men [37]. A negative correlation to muscle strength was found for females, indicating that peak torque angles occurred later in the range of motion as muscle strength decreased [37]. Lastly, when comparing strength training programs, an agility training program was found to improve leg muscle reaction times in response to perturbation the most, whereas agility and isokinetic training most effectively improves the time to peak muscle torque [39].

Kinetic and kinematic characteristics of landing

When analyzing human movement and noncontact injuries we must consider several forces that act on a body, including weight, ground reaction force, joint reaction force, muscle force, elastic force, and inertia force. Additionally, the biomechanical principle of impulse summarizes potential errors in landing techniques. Impulse is defined as the size of a force multiplied by the time of that force's application. One has ideal impulse if a force is absorbed over a longer period of time. To do so, joints must go through a complete range of motion to ensure the maximum time available to absorb that force was used [40]. Applying this information to potentially hazardous knee injuries is the degree of knee flexion on landing and impact velocity. Lesser degrees of knee flexion may be associated with increased peak vertical or ground reaction forces [41]. The lower the ground reaction forces the greater the impulse and the less chance of injury. Researchers found that lowered ground reaction forces demonstrate an increase of the angular displacement of the knee after ground contact and increased hamstring activity [10].

Gender differences do exist when athletes perform athletic maneuvers, such as cutting and landing from a jump. Women tend to land with the knee [42–47] and hip [44] in a more extended position, and therefore subject themselves to higher forces per body weight during the impact of landing [42]. As illustrated in Figure 1, females tend to demonstrate greater valgus angles than males at ground contact, suggesting that the load on the ACL increases as knee valgus increases [44,48].

Likewise, skilled and unskilled individuals land from a jump with notable differences [49–51]. Alterations in strategy and landing characteristics are often attributed to skill. Skilled individuals may exhibit increased ankle plantar flexion [49,50], knee flexion [50], hip flexion [50], and muscle preactivity [50], which allow for more movement after ground contact and more time to distribute the impact forces, resulting in lowered ground reaction forces [40,49–51]. Also, these landing forces may change throughout the athlete's conditioning as their periodization cycle changes [52]. Lastly, horizontal jumping uses the hip, knee, ankle joint, and their musculature differently than that of vertical jumping [53].

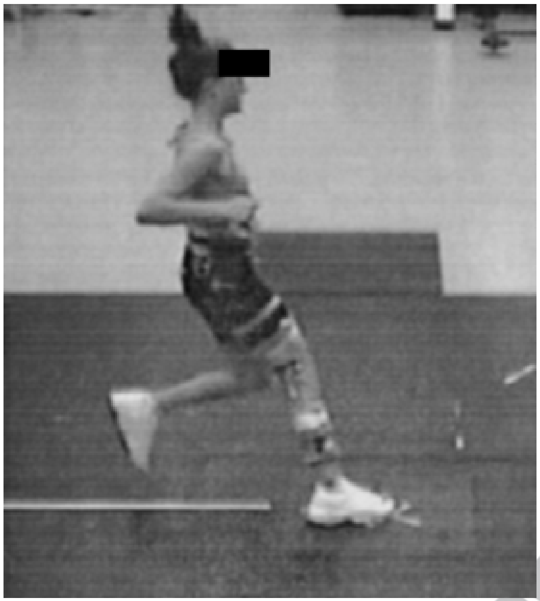
Quadriceps and hamstrings

Studies have reported the average angle of knee flexion at the time of injury to be 22° [43,54]. At knee flexion, angles from 0–45° quadriceps contractions strain the ACL [13,16,55–59], particularly at heel strike [43]. Focusing on knee mechanics during muscle loading, the

Figure 1. Position of vulnerability

Females tend to demonstrate greater valgus angles at ground contact than males.

Figure 2. Pretest cutting position



Cutting position before the 8-week neuromuscular training program.

patella-tendon-tibia shift angle (the angle between the patella tendon and the longitudinal axis of the tibia) increases as knee flexion decreases, indicating that the magnitude of the shear force on the tibia applied by the patellar tendon increases [60,61]. Eccentric quadriceps forces on the anterior tibia have been contented to reach 5000N when knee flexion is between 10–30° [55]. Another reason for increased quadriceps activity is small hip flexion angles. Quadriceps activity decreases with increased hip flexion [59,62]. This is seen in females most often, who tend to activate their quadriceps more than males [44], suggesting that the ACL can be torn in a noncontact situation when the quadriceps eccentrically contract because of the shear force exceeding the reported tensile strength of the ACL [63]. Injury to the ACL may occur when small knee flexion angles are coupled with an inappropriate amount of hamstring counterforce to resist anterior translation [16,19,43, 60,64,65].

The hamstrings, considered agonists to the ACL because of their protective mechanism of reducing anterior translation, are most influential when the knee is flexed to at least 15–30° [16,66]. Within this range of flexed positions, the line of hamstring pull is more advantageous in achieving a posterior pull of the tibia as opposed to the line of pull when the knee is extended [16,43,66]. Considering the influence of quadriceps activity on anterior tibial translation, it is important for the hamstrings to counter this movement, particularly in the presence of an abnormal quadriceps/hamstring strength ratio [67]. Thus, the contraction of the quadriceps alone may be enough to rupture the ACL, leaving the hamstrings to assume the important role of maintaining joint stability [60].

In summary, females tend to activate their quadriceps near full extension of the knee with little hamstring activity and to land with smaller angles of hip flexion and larger angles of valgus compared with males. The combined effects from these findings suggest that women are at an increased risk of ACL injury.

Future directions

Preventative programs

There is limited research regarding preseason strength and flexibility measures in female athletes [68] and inconclusive evidence to support possible predictive factors contributing to ACL ruptures [69–71]. Likewise, to date, one prevention program was studied that specifically addresses these neuromuscular issues in females [72]. A jump-training program lasting for 6 weeks included various plyometric exercises and emphasized proper jumping techniques. The investigators found lower mean landing forces (N), a significant decrease in adduction or abduction forces, and a significant increase in isokinetic hamstring strength and hamstring-quadriceps peak torque ratios for the trained group, which consisted of 11 female high school volleyball players, *versus* the control group comprising of nine untrained matched males [72]. Because of these favorable results, this program was implemented during soccer, volleyball, and basketball preseasons among 1263 high school athletes, who were monitored for knee injuries throughout their respective seasons. There were 14 serious knee injuries throughout the respective season. The authors

Figure 3. Post-test cutting position

Cutting position after the 8-week neuromuscular training program.

claim that the reduction of serious knee injuries is most likely because of their preseason preventative training program [73].

To ensure the effectiveness of preventative training programs, many more variables need to be assessed. Knee kinesthesia and joint position sense, postural control variables, hip and thigh muscle strength, lower extremity joint kinematic variables, muscle activation, and selected vertical ground reaction forces during landing would ideally be evaluated prospectively to determine which variables change as a result of a neuromuscular training program. Proposed preventative studies would examine the effects of a neuromuscular training program on mechanisms deficient in female athletes (hip and leg muscle strength, rate of muscular force generation, and landing stability) and determine if induced changes in these variables result in adaptations to selected landing variables (knee and hip flexion angles, sway on ground contact, vGRF on ground contact).

A current 4-year study is examining the influence of an 8-week neuromuscular training program on the previously mentioned mechanisms and variables found to be deficient in females [7–11]. The neuromuscular training program is designed to improve hip abduction/adduction strength, quadriceps and hamstring strength, joint kinesthesia and joint position sense, knee stability, improvement of functional strategies, and absorption of landing forces using plyometric landing techniques. It is believed that female athletes participating in the current neuromuscular training program will reveal significant muscular and biomechanical adaptations, resulting in more efficient landing strategies. Figure 3 shows alterations in cutting strategies after the 8 week neuromuscular training program.

Retraining motor patterns, landing strategies, and improving specific leg muscle strength with a neuromuscular training program may result in more efficient landing techniques for females, avoiding vulnerable knee extension angles on ground contact from jumping or cutting activities. The elimination of awkward landing positions and improvements in muscle activation patterns will likely reduce the incidence of ACL injuries in females.

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