The Role of Proprioception in the Management and Rehabilitation of Athletic Injuries

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ABSTRACT

Rehabilitation continues to evolve with the increased emphasis on patient management and proprioceptive training. Proprioception can be defined as a specialized variation of the sensory modality of touch that encompasses the sensation of joint movement (kinesthesia) and joint position (joint position sense). Numerous investigators have observed that afferent feedback to the brain and spinal pathways is mediated by skin, articular, and muscle mechanoreceptors. Examining the effects of ligamentous injury, surgical intervention, and proprioceptively mediated activities in the rehabilitation program provides an understanding of the complexity of this system responsible for motor control. It appears that this neuromuscular feedback mechanism becomes interrupted with injury and abnormalities, and approaches restoration after surgical intervention and rehabilitation. Rehabilitation programs should be designed to include a proprioceptive component that addresses the following three levels of motor control: spinal reflexes, cognitive programming, and brainstem activity. Such a program is highly recommended to promote dynamic joint and functional stability. Thus far, current knowledge regarding the basic science and clinical application of proprioception has led the profession of sports medicine one step closer to its ultimate goal of restoring function.

The proper management of athletic-related injuries and orthopaedic lesions can be complex in the sports medicine setting. One of the most challenging aspects to the clinician is understanding the role of proprioceptively mediated neuromuscular control after joint injury and its restoration through rehabilitation. Proprioception contributes to the motor programming for neuromuscular control required for precision movements and also contributes to muscle reflex, providing dynamic joint stability. The coupling effect of ligamentous trauma resulting in mechanical instability and proprioceptive deficits contributes to functional instability, which could ultimately lead to further microtrauma and reinjury (Fig. 1). Achieving functional and sport-specific activities after musculoskeletal trauma and rehabilitation can be enhanced significantly if proprioception is addressed and instituted early in the treatment program.

In addition to the mechanical restraint provided by articular structures, it has been observed that ligaments provide neurologic feedback that directly mediates reflex muscular stabilization about the joint.26 The inclusion of proprioception in the rehabilitation program should be based on the preceding finding and not on anecdotal evidence without an understanding of the neuromuscular mechanism. This understanding, coupled with a base of knowledge regarding the current research on proprioception, is necessary for sports medicine practitioners to optimize treatment programs for athletes.

THE ROLE OF PROPRIOCEPTION

Numerous investigators have provided definitions regarding the terminology of joint sensation, or proprioception and kinesthesia.3,26 Most contemporary authorities define proprioception as a specialized variation of the sensory

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Role of Proprioception in Athletic Injuries

The concept of proprioception is based on the fact that neural feedback to the CNS is mediated by cutaneous, muscle, and joint mechanoreceptors (Fig. 3). When examining the neural composition of joints, Hilton's law states that joints are innervated by articular branches of the nerves supplying the muscles that cross the joint. In addition to proprioceptive mechanoreceptors, articular structures also include nociceptive free nerve endings.

Activation of joint mechanoreceptors is triggered by the deformation and loading of the soft tissues that compose the joint. This neural stimulation travels to the CNS for integration via cortical and reflex pathways. These mechanoreceptors demonstrate adaptive properties depending on a particular stimulus (Table 1).

Quick-adapting joint mechanoreceptors, such as the Pacinian corpuscles, decrease their discharge rate to extinction within milliseconds of the onset of a continuous stimulus. The Ruffini ending, Ruffini corpuscles, and the Golgi tendon-like organs that are referred to as the slow-adapting mechanoreceptors, continue their discharge in response to a continuous stimulus. The properties of the

Figure 1. Functional stability paradigm depicting the progression of functional instability of the shoulder joint due to the interaction between mechanical instability and decreased neuromuscular control. (Reprinted with permission from Lephart and Henry.23)

Figure 2. Neuromuscular control pathways. (Reprinted with permission from Lephart and Henry.)

Figure 3. Schematic representation of proprioceptive mechanoreceptors: a) Ruffini ending, b) Pacinian corpuscle, c) muscle spindle receptors, and d) Golgi tendon organs. (Adapted from Willis and Grossman.)
quick-adapting mechanoreceptors lead to the notion that they mediate the sensation of joint motion because they are very sensitive to changes in position. Muscular mechanoreceptors and Ruffini ending joint receptors are slow-adapting mechanoreceptors and are thought to mediate the sensation of joint position and changes in position because they are maximally stimulated at specific joint angles. One form of the slow-adapting receptors are the complex, fusiform muscle spindle receptors found within skeletal muscle. The muscle spindle receptor functions to measure muscle tension over a large range of extrafusal muscle length (Table 2). It has been suggested that muscle and joint mechanoreceptors are complementary to each other in providing afferent input in regard to limb position.4

This relationship between muscle and joint mechanoreceptors has been supported by the identification of the neural components necessary for the sensation of motion (rapidly adapting receptors, e.g., Pacinian corpuscles), joint position and acceleration (slow-adapting receptors, e.g., Ruffini endings and Ruffini corpuscles), and pain (free nerve endings) within ligamentous, cartilaginous, and muscular structures of the joints. The spindle receptors found within the muscle are composed of a small bundle of modified muscle fibers called intrafusal fibers, to which the endings of several sensory nerves are attached. The extrafusal fibers that form the bulk of the muscle are responsible for generating force and are innervated by the alpha-motor neurons whereas the intrafusal fibers are innervated by the gamma-motor neurons. In the case of muscle contraction, alpha-gamma co-activation is believed to be the mechanism through which muscle length and tension are monitored.27 Activation of gamma-motor neurons allow the readjustment of spindle sensitivity in the case where extrafusal fibers are shortened. This allows the spindles to be functional at all times during a contraction. When a muscle is loaded beyond an anticipated level, intrafusal fiber shortening occurs to a greater degree than extrafusal shortening. Stretching of the spindles in the central region causes a burst of excitatory postsynaptic potentials from spindle afferents. These signals summate with the alpha-motor neurons from descending pathways, thereby increasing force production.27

With respect to changes in muscle and tendon tension, the Golgi tendon organs function as a protective mechanism. The Golgi tendon organs are located within the tendons of muscles and are recruited when muscle contraction pulls on the tendon, which straightens the collagen bundles and distorts the receptor endings of the afferent neurons.27 This distortion increases the discharge rate of action potentials of these receptors that travel and synapse on spinal interneurons that project to motor neurons. Increased activity of the Golgi tendon organ afferents result in the inhibition of the motor neurons innervating the muscles that were stretched while exciting the motor nerves of the antagonistic muscles.

Studies have demonstrated the detrimental effect on reflex joint stabilization as a result of joint injury.30.31 The contribution of musculotendinous receptors over joint receptors to the proprioceptive reflex remains a controversial issue in the literature. The ability to quantify proprioceptive deficits is a vital component to the evaluation of joint injury that may attempt to answer a number of clinical research questions.

**CLINICAL QUESTIONS**

Clinical application of proprioception research findings must be achieved at various levels of care for the management of orthopaedic lesions. A thorough understanding of proprioception assessment techniques will aid the clinician and orthopaedic surgeon to apply what is currently known concerning the nontraumatized joint to muscular, ligamentous, and cartilaginous injury. Establishing the effects of musculoskeletal trauma on joint position sensibility and neuromuscular control assists the need for critical decision-making regarding the appropriateness of various forms of treatment. From this point, it is known that surgical intervention plays an important role in the restoration of mechanical joint stability but its effects on proprioception pathways require further clarification. Finally, rehabilitation activities incorporating principles that stimulate the different levels of motor control to facilitate the return to function should be examined not only for its theoretical basis but also for its practical applicability.

The assessment of neuromuscular control includes the measurement of cortical, spinal reflex, and brainstem pathways. The evaluation of this complex neuromuscular system as different components allows a more detailed explanation of afferent control mechanisms. As defined previously, kinesthesia and joint position sense are

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**TABLE 1**

<table>
<thead>
<tr>
<th>Receptor type</th>
<th>Location</th>
<th>Adaptation rate</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>I, Ruffini endings</td>
<td>Joint capsule and ligaments</td>
<td>Slow</td>
<td>Reflex (stretch reflex)</td>
</tr>
<tr>
<td>II, Pacinian corpuscle</td>
<td>Joint capsule</td>
<td>Slow</td>
<td>Reflex</td>
</tr>
<tr>
<td>IV (a), Unmyelinated free nerve endings</td>
<td>Ligaments (and related muscles)</td>
<td>Slow</td>
<td>High frequency vibration</td>
</tr>
</tbody>
</table>

* Modified from Freeman and Wyke.11

**TABLE 2**

<table>
<thead>
<tr>
<th>Receptor type</th>
<th>Location</th>
<th>Adaptation rate</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tendons</td>
<td>Slow</td>
<td>Reflex</td>
<td></td>
</tr>
<tr>
<td>Muscle</td>
<td>Slow</td>
<td>Reflex (stretch reflex)</td>
<td></td>
</tr>
</tbody>
</table>

* Modified from Freeman and Wyke.11
components of proprioception. Functionally, kinesthesia is assessed by measuring threshold to detection of passive motion while joint position sense is assessed by measuring reproduction of passive positioning and reproduction of active positioning. When tested at a slow angular velocity (0.5 to 2 deg/sec), threshold to detection of passive motion as well as the reproduction of passive positioning is thought to selectively stimulate Ruffini or Golgi-type mechanoreceptors. Because the test is performed passively, it is believed to maximally stimulate joint receptors, thereby relying on the cortical pathway in the neuromuscular control system. After ligament injuries, passive joint sensibility testing is often chosen to assess afferent activity because muscle activity is negated. Stimulation of both joint and muscle receptors is done by the reproduction of active positioning, which provides a more functional assessment of the afferent pathways.

The evaluation of reflex capabilities is often assessed by measuring the latency of muscular activation to involuntary perturbation via electromyographic interpretation. The ability to quantify the sequencing of muscle firing can provide a useful tool for the assessment of asynchronous neuromuscular activation patterns that may predispose an articulation to overuse trauma.

Functional assessment of the combined peripheral, vestibular, and visual contributions to neuromuscular control is best accomplished through the use of balance and postural sway measurements for the lower extremity. The availability of stabilometric methods and instrumentation can provide a relatively accurate index for these measures.

To reiterate this understanding of the proprioception mechanism, the clinician must apply the available knowledge to try to delineate the effects of orthopaedic injury, surgical reconstruction, and rehabilitation on the various afferent pathways. Specifically, clinical research aimed at determining the effects of injury, surgery, and rehabilitation on joint position sensibility, neuromuscular control, as well as balance and postural sway can provide a solid foundation for the development of a testing model for the knee, ankle, and shoulder that attempt to address these issues.

KNEE PROPRIOCEPTION

Numerous studies have been performed that examined the role of proprioception in the knee joint. It has been found that damage to articular structures, such as the ACL and meniscus, in addition to osteoarthritic changes disrupts articular structures containing mechanoreceptors. The disruption in the cortical pathway, therefore, results in an alteration in joint position sense and kinesthesia. Barrack et al. and Skinner et al. observed decreased kinesthesia with increasing age and ACL disruption. Joint position sensibility decrements have also been documented as a result of osteoarthritic changes in the knee.

Deficits in the neuromuscular reflex pathway may have a detrimental effect on this motor control system’s role as a protective mechanism in acute knee injury. The initiation of the reflex arc stimulated by mechanoreceptors and muscle spindle receptors occurs at a faster rate than signals induced by nociceptors (70 to 100 m/sec versus 1 m/sec). This suggests that proprioception may play a more significant role than pain impulses in preventing injury in the acute setting. However, the incidence of reinjury and the cause of chronic injuries may be attributed, to a greater extent, to proprioceptive deficits. These deficits may be induced by partial deafferentation as a result of initial knee injury and may also contribute to chronic joint disease through a decrease in joint afferents. This phenomenon has been observed by Beard et al. in subjects with arthroscopically confirmed ACL deficiency. A significant deficit in reflex activation of the hamstring muscles after a 100 N anterior shear force in a single-legged closed kinematic chain position was identified, as compared with the contralateral uninjured limb. Furthermore, Solomonow et al. found that a direct stress applied to the ACL resulted in reflex hamstring activity, thereby contributing to the maintenance of joint integrity.

Although Barrack et al. demonstrated a proprioceptive deficit after ACL disruption, it appears that kinesthetic awareness may be partially restored after ACL reconstruction. Kinesthesia has been reported to be restored after surgery as detected by the threshold to the detection of passive motion in the midrange of motion (45°). However, a longer threshold to the detection of passive motion was observed in the ACL reconstructed knee compared with the contralateral uninjured knee when tested at 15° of flexion. Lephart et al. found similar results in patients after either arthroscopically assisted patellar-tendon autograft or allograft ACL reconstruction. This evidence suggests that kinesthesia may have returned in the midrange of motion after ACL reconstruction and appears to be more sensitive in the near-terminal range of motion.

The importance of incorporating a proprioceptive element in any comprehensive rehabilitation program is justified based on the results of these studies. Proprioceptive deficits may predispose an athlete to reinjury through decrements in the neuromuscular pathways resulting in the inhibition of complete rehabilitation.

ANKLE PROPRIOCEPTION

Chronic ankle instability as a result of partial deafferentation of articular mechanoreceptors with joint injury was first postulated by Freeman et al. They observed that a decrease in the ability to maintain a one-legged stance occurred in the sprained ankle versus the contralateral uninjured ankle. The effect of unilateral ankle sprains on cortical pathway measures of proprioception have been investigated by Garn and Newton, who measured the ability of a subject to properly sense a passive movement or no movement state in the sagittal plane. Deficits in the ability to actively replicate passive ankle and foot positioning in this plane was reported by Glencross and Thornton while testing the sprained ankle versus the contralateral uninjured ankle. Gross recently reported that an increased probability of reinjury occurs as a result of a decrease in sensory input from joint.
receptors, leading to abnormal body positioning and diminished postural reflex responses. It was also found by Konradsen and Ravn \[21\] that chronic ankle instability resulted in a prolonged peroneal reaction time in response to a sudden inversion stress when compared with age-matched controls. Partial deafferentation resulting in diminished reflex joint stabilization may contribute to these findings.

The development of high technologic systems to assess the effects of musculoskeletal injury on balance has occurred in an attempt to quantify both static and dynamic components of proprioception. \[18\] The method of evaluation is based on the notion that damage to joint proprioceptors after injury to the lateral ligamentous complex of the ankle diminishes afferent feedback from the injured joint, thereby resulting in increases in postural sway. \[10\] To date, however, documented evidence exists concerning the alterations in postural sway after ankle injury using subjective evaluation (i.e., Romberg test). No increases in postural sway were observed by Tropp and Odenrick \[32\] when comparing a group of soccer players with previous ankle sprains to a control group of uninjured soccer players. Furthermore, no differences in postural sway were found between the involved and uninvolved ankles in a group of soccer players with a history of unilateral, recurrent ankle sprains. \[32\] However, significant increases in postural sway were observed by Cornell and Murrell \[9\] when comparing patients with acute ankle sprains with uninjured controls as long as 2 years after their injuries.

The effects of surgical reconstruction for functional ankle instability on proprioception pathways as measured through joint position sensibility or balance and postural sway assessments have not yet been thoroughly investigated. Empirical evidence exists suggesting that proprioceptive training techniques after acute and chronic ankle injuries are highly effective. In addition, ankle wrapping and bracing have also been suggested to have a proprioceptive benefit. However, this notion remains untested and, therefore, unproven.

**SHOULDER PROPRIOCEPTION**

Placement of the hand is a necessary task during activities of daily living in addition to sport-specific patterns. Joint position sensibility has not only played a role in the maintenance of dynamic shoulder stability but has also been shown to demonstrate alterations after injury. Smith and Brunolli \[29\] have observed deficits in shoulder kinesthesias and joint position sense in male subjects with unilateral, traumatic, recurrent anterior shoulder instabilities. In a similar group of patients, Lephart and coworkers \[28\] also demonstrated proprioceptive deficits in the pathologic shoulder as compared with the contralateral normal shoulder.

In addition to alterations in the cortical pathway, Glousmann and coworkers \[14\] observed changes in the electromyographic pattern in baseball pitchers demonstrating shoulder instability. Reduction in neuromuscular activation of the pectoralis major, subscapularis, and latissimus dorsi muscles was found to contribute to anterior instability through a decrease in the normal internal rotation force required for this motion. \[14\] Compensatory increases in biceps and supraspinatis muscle activity were also discovered in an attempt to restore anterior stability. This loss in the normal synchronization of neuromuscular firing patterns in the unstable shoulder has, therefore, been attributed to altered joint kinematics resulting in repetitive microtrauma. \[14\]

Surgical intervention has been shown to partially restore joint proprioception through the repair of traumatized tissue. Partial restoration of kinesthesia has been observed in patients undergoing capsulolabral reconstruction. \[35\] This observation of enhanced proprioception centers around the procedural techniques used that promoted modification of joint sensation. Because this procedure modifies soft tissue dissection, there was a minimal loss of intact mechanoreceptors and a promotion of repopulation. In addition, the use of the capsular shift in these shoulder instability cases, which tightens the capsule, “retensions” the soft tissue and most likely facilitated proprioception function. It may be through this procedure of retensioning that mechanoreceptor-containing shoulder capsuloligamentous structures transmit afferent information at a more functional level regarding joint position sensibility.

Regaining dynamic neuromuscular control of the unstable or postoperative shoulder is of primary importance for the return of an athlete to functional activity. Rehabilitation exercises should focus on the importance of incorporating joint position sensibility and reflexive-type contractions into the therapy program. The inclusion of reflexive-mediated activities is based on the recent findings of Guanche and coworkers \[17\] who have observed three different articular branches of the axillary nerve innervating the shoulder capsule that provide a primary reflex arc to the biceps, supraspinatis, infraspinatis, deltoid, and subscapularis muscles in the feline model. This reflexive contraction has been attributed to providing a dynamic muscular restraint to the intact shoulder capsule. \[17\] Because the shoulder model in this study was that of a weightbearing joint, the closed kinetic chain principle is needed in upper extremity rehabilitation.

**REHABILITATION**

The objectives of proprioceptive rehabilitation are to retrain altered afferent pathways to enhance the sensation of joint movement. Proprioceptively mediated neuromuscular control of joints takes into account three distinct levels of motor activation within the CNS. Reflexes at the spinal level mediate movement patterns that are received from higher levels of the nervous system. This action provides for reflex joint stabilization during conditions of abnormal stress about the articulation and has significant implications for rehabilitation. \[30\] The use of exercises that facilitate dynamic joint stabilization may result in the improvement of this neuromuscular mechanism.

The second level of motor control, located within the brainstem, receives input from joint mechanoreceptors, vestibular centers, and visual input from the eyes to maintain posture and balance of the body. Reactive
neuromuscular activities that allow this pathway to process input from the aforementioned forms of afferent stimuli can be used to enhance brainstem function.

The highest level of CNS function (motor cortex, basal ganglia, and cerebellum) provides cognitive awareness of body position and movement in which motor commands are initiated for voluntary movements. Use of the cortical pathway allows movements that are repeated and stored as central commands to be performed without continuous reference to consciousness. Kinesthetic and proprioception training are such types of activity that can enhance this function.

Incorporating the three levels of motor control into activities to address proprioceptive deficiencies should be initiated early during the rehabilitation process. Encouraging maximum afferent discharge to the respective CNS level must be the goal in stimulating joint and muscle receptors. To stimulate reflex joint stabilization, which emanates from the spinal cord, activities should focus on sudden alterations in joint positioning that necessitate reflex neuromuscular control. Enhancing motor function at the brainstem level can be achieved by performing balance and postural activities, both with and without visual input. Maximally stimulating the conversion of conscious to unconscious motor programming can be achieved by performing joint positioning activities, especially at joint end ranges. Simple tasks such as balance training and joint repositioning should begin early in the rehabilitation program and should become increasingly more difficult as the patient progresses. Regaining joint sense awareness to initiate muscular reflex stabilization to prevent reinjury should be the primary objective once the final stage of rehabilitation is reached.

Some contemporary authors believe that adaptations that occur during rehabilitation are related to (mediated by) feed-forward processing and are less a function of enhanced afferent pathways. This theory suggests that fast movements are controlled by advance information known about the task, while concurrent proprioceptive feedback is relatively less important. Feedback is used primarily at the cortical level to determine the success or failure of that movement and to a lesser extent at the subcortical level for directing the movement. With repetition, the cerebral cortex can determine the most effective motor pattern for a given task, based on the proprioceptive information of previous attempts. Biofeedback training appears to use the feed-forward learning process. However, there is still controversy regarding the contribution of afferent feedback in feed-forward processing.

Following is an example of a shoulder rehabilitation protocol that has been designed using the principles outlined in this paper for reestablishing proprioception and neuromuscular control.

Reestablishing Proprioception and Neuromuscular Control in the Shoulder

Proprioception training of the upper extremity has been incorporated into the rehabilitation program to a lesser extent than that of the lower extremity. Because the primary sport-specific activity of the upper extremity is the throwing motion, refined joint positioning and repositioning of the shoulder is vital. Therefore, mechanoreceptor activity plays an important role in both performance and dynamic shoulder stabilization. To maximally restore proprioception and neuromuscular control, it is recommended that the following progression of activities be conducted to allow the return of an athlete to functional levels: 1) joint position sense and kinesthesia, 2) dynamic joint stabilization, 3) reactive neuromuscular control, and 4) functionally specific activities. Such a progression allows the rehabilitation program to address the integration of spinal reflex, cognitive, and brainstem pathways to focus on scapular stabilization, glenohumeral stabilization, humeral motion, and neuromuscular control.

Position sensibility activities are designed to restore joint position sense and kinesthesia (Fig. 4). These exercises stimulate cognitive level processing through the use of such an exercise as glenohumeral repositioning both with and without visual input and proprioceptive neuromuscular facilitation patterns performed with manual resistance.

Dynamic stabilization activities are designed to stimulate muscular coactivation. In the shoulder, such activities include axial loading of the glenohumeral joint promote coactivation of the glenohumeral and scapulothoracic force couples (Fig. 5). The use of such activities as upper extremity balance training results in muscular coactivation.

Ultimately, the integration of both spinal and cognitive levels can be accomplished by the use of neuromuscular control exercises such as plyometrics. Shoulder plyometric exercises stimulate reflexive activity through the facilitation of the myotatic reflex via the release of stored elastic energy. Such activities stimulate reflex joint stabilization, which are critical to the overhead athlete (Fig. 6).

Once joint sensibility and dynamic muscle joint stabilization are restored, progression to functionally specific activities can be accomplished. Functionally specific activ-
ilities are designed to restore functional motor patterns necessary for successful performance of the overhead athlete (Fig. 7).

The integration of these levels is a necessary component of the rehabilitation program to provide proper neuromuscular control and functional stability of the joint. Completion of the progressive neuromuscular control rehabilitation program minimizes the risk of reinjury and promotes a greater chance of successful return to competition.

With respect to the lower extremity, mechanoreceptors located within the joints are most functionally stimulated when the extremity is positioned in a closed-kinetic chain orientation and perpendicular axial loading of the joint is permitted. These exercises should be performed at various positions throughout the full range of motion because of the difference in the afferent response that has been observed at different joint positions.

FUTURE DIRECTIONS

The numerous investigations cited in this review have attempted to present an understanding and a rationale behind the use of proprioception exercises in rehabilitation. However, this pool of knowledge has opened the door to many more questions concerning proprioceptively mediated neuromuscular control. Evidence regarding the effects of rehabilitation on proprioception has yet to be verified. In addition, the effects of tissue regeneration on neuromuscular pathways is an area that also needs to be investigated. The establishment of this relationship between proprioceptive deficits and motor control attempts to incorporate basic science and clinical findings into a practical rehabilitation exercise prescription. Finally, prospectively evaluating the effects of ligamentous injury, surgical reconstruction, and rehabilitation will help to justify the means through which articular lesions are managed. The research presented thus far puts the clinician one step closer to optimizing clinical decision-making.
of the rehabilitation protocol. This process of understanding leads to the ultimate goal of restored function.

REFERENCES

Gender Differences in Strength and Lower Extremity Kinematics During Landing

Scott M. Lephart, PhD, ATC; Cheryl M. Ferris, MEd, ATC; Bryan L. Riemann, PhD, ATC; Joseph B. Myers, PhD, ATC; and Freddie H. Fu, MD, ScD

This study evaluated kinematic, vertical ground reaction forces, and strength variables in healthy collegiate female basketball, volleyball, and soccer players compared with matched male subjects. Thirty athletes did single-leg landing and forward hop tasks. An electromagnetic tracking device synchronized with a force plate provided kinematic data and vertical ground reaction force data, respectively. Maximum angular displacement and time to maximum angular displacement kinematic variables were calculated for hip flexion, abduction, rotation, knee flexion, and lower leg rotation. Vertical ground reaction force data normalized to body mass provided impulse, maximum force, time to maximum force, and stabilization time variables. An isokinetic device measured quadriceps and hamstring peak torque to body mass at 60°/second. With both tasks, females had significantly less knee flexion and lower leg internal rotation maximum angular displacement, and less knee flexion time to maximum angular displacement than males. For the single-leg land, females had significantly more hip internal rotation maximum angular displacement, and less lower leg internal rotation time to maximum angular displacement than males. For the forward hop, females had significantly more hip rotation time to maximum angular displacement than males. Females also had significantly less peak torque to body mass for the quadriceps and hamstrings than males. Weaker thigh musculature may be related to the abrupt stiffening of the knee and lower leg on landing in females.

The rate of injury to the anterior cruciate ligament in the population in the United States exceeds one in every 3000 persons.25 Of these physically active individuals, females sustain anterior cruciate ligament ruptures two-to-eight times more frequently than their male counterparts with risk of injury increasing with participation in soccer and basketball.1,10,11,18,20,25 Many noncontact mechanisms of injury have been proposed to be responsible for this disproportionate injury rate.3,12

Numerous studies have focused on neuromuscular and biomechanical variables.4–7,13,15,17,22,26,31,33 Although these studies have shown gender-related differences, there is a lack of consistency in study designs and variables re-
ported. From a neuromuscular perspective, females have been identified as being quadriceps dominant, where the quadriceps are the first muscle to activate in response to injury mechanism perturbations and selective athletic maneuvers. This tendency may result in excessive stress placed on the anterior cruciate ligament because an unopposed quadriceps contraction will displace the tibia anteriorly. Additionally, one study found females to have reduced proprioception, which may allow excessive joint movement before dynamic stabilizers can effectively protect the joint. Two biomechanical studies focused on knee flexion angles at ground contact, suggesting that there is a relationship between this angle and the risk for anterior cruciate ligament injury. Another study found that high ground reaction forces are gender-specific accompanying landing in female athletes.

Although the above studies reported valuable findings and began to establish a gender-related profile, they lack data concerning motion of the lower extremity that occurs after ground contact that may provide additional information about fundamental mechanisms contributing to the risk of anterior cruciate ligament injuries. Of particular concern is the effectiveness of the lower extremity to dissipate the forces generated during landing. If impact force at the knee is applied during a short time, and without accommodating joint movement, the body has less of an opportunity to attenuate forces. To date, a few studies have focused on the maximum angular displacement or the difference between the ground contact and peak angles; however, a gender comparison was not conducted. If the amount of time to maximum angular displacement is maximal, and if the maximum angular displacement is large, then impact forces will be attenuated. Theoretically, this biomechanical pattern should allow optimal conditions to prevent injury.

The current study evaluated lower extremity kinematic patterns, vertical ground reaction forces, and muscle strength in collegiate female basketball, volleyball, and soccer players compared with matched recreational male athletes.

**MATERIALS AND METHODS**

**Subjects and Research Design**

Fifteen female Division I basketball, volleyball, and soccer athletes (age, $19.3 \pm 1.2$ years; height, $174.5 \pm 6.8$ cm; weight, $68.0 \pm 9.0$ kg) and 15 matched, according to age and activity level, male recreational athletes who previously had played organized basketball or soccer (age, $21.26 \pm 1.55$ years; height, $177.62 \pm 6.34$ cm; weight, $75.45 \pm 8.53$ kg) participated in this study. All subjects were injury-free, signed informed consent, and attended one testing session. During this session, each subject completed two landing tasks and a strength assessment.

Kinematic data were collected using the Motion Monitor Motion Analysis System (Innovative Sports Training, Chicago, IL) electromagnetic tracking device. Four electromagnetic motion analysis sensors were secured to subjects using prefabricated neoprene cuffs with clips to the desired limbs. Sensors were placed over the upper thorax, sacrum, lateral thigh, and lateral lower leg to evaluate hip flexion, rotation and abduction, knee flexion, and lower leg rotation at 100 Hz. Maximum angular displacement and time to maximum angular displacement were calculated for the aforementioned joint motions. Maximum angular displacement was defined as the difference between the ground contact angle and the peak angle attained after ground contact. The time to maximum angular displacement was defined as the time to achieve maximum angular displacement from ground contact.

Vertical ground reaction forces were assessed using a Bertec force plate (Bertec Corporation, Columbus, OH) that was synchronized with the motion monitor. Vertical ground reaction forces were sampled at 1000 Hz. Landing forces, specifically maximum vertical force and time to maximum vertical force, were evaluated at ground contact, which was defined as 1% of body mass. The vertical ground reaction force also was used to measure the time to maximum force and impulse. Impulse was calculated and defined as the area under the curve in a time interval from which the vertical ground reaction force exceeds 10% of the subjects’ body mass to 0.1 second after ground contact. A sequential estimation using an algorithm defined by Colby et al was used to determine the stabilization time of the vertical ground reaction force (Fz), mediolateral force (Fx), and anteroposterior force (Fy). Stabilization time is calculated by the interval from ground contact to when the
vertical reaction force is reduced to 5% of the subject’s body weight.

The landing task order was counterbalanced between subjects. The first subject was assigned randomly to first do single-leg landing, followed by the forward hop. The order of performance of the landing tasks then was alternated between subjects. Both landing tasks began with subjects standing with their hands on their hips and balancing on the dominant leg. The dominant leg was defined as the leg with which subjects prefer to kick a ball. The verbal cue of jump signaled the subjects to hop onto the X marked on the force plate. For single-leg landing (Fig 1), subjects hopped off a 20 cm platform. The platform was placed 11 cm from the back edge of a force plate. During the forward hop task (Fig 2), subjects started at a distance of 45% of their height away from the X marked on the force plate. An obstacle was placed equidistant between the starting line and X. Subjects did three practice trials followed by four test trials of each task. An investigator was present at all times to prevent falling or other potential adverse events.

Isokinetic Assessment

Isokinetic strength data were recorded with the Biodex System III Dynamometer (Biodex Medical Inc, Shirley, NY) to assess peak torque to body weight of the quadriceps and hamstrings. Torque values were adjusted automatically for gravity by the Biodex Advantage Software v. 3.2 (Biodex Medical Inc). Calibration of the Biodex dynamometer was done according to the specifications outlined in the manufacturer’s service manual.

For knee testing, subjects sat in a comfortable upright position on the Biodex dynamometer chair and were secured using thigh, pelvic, and torso straps to minimize extraneous body movements and momentum. The lateral femoral condyle was used as the bony landmark for aligning the axis of rotation of the knee with the axis of rotation of the dynamometer. Practice trials of three submaximal and three maximal repetitions preceded the test to ensure unrestricted movement through the range of motion and subject familiarization. Before the test trials, subjects were instructed to fold their arms across their
chest and give maximal effort. Subjects did five iso-
kine
etic concentric knee flexion and extension repeti-
tions at 60°/second of their dominant limb.

RESULTS
All data were analyzed with a one-way analy-
sis of variance (ANOVA) and the significance
level was set at 0.05 a priori. For the single-leg
landing task (Table 1), females revealed sig-
ificantly greater hip internal rotation (F =
16.0; p = 0.000), less knee flexion (F = 10.6;
p = 0.003), and less lower leg internal rotation
(F = 11.4; p = 0.002) maximum angular dis-
placement compared with the male subjects.
The females also had significantly less time to
maximum angular displacement of knee flex-
ion (F = 6.9; p = 0.014) and lower leg inter-
nal rotation (F = 7.3; p = 0.012).

For the forward hop landing task (Table 1),
the females had significantly less knee flexion
(F = 6.8; p = 0.014) and lower leg internal ro-
tation (F = 0.1; p = 0.005) maximum angular
displacement compared with the male sub-
jects. The females had significantly more time
to maximum angular displacement for hip in-
ternal rotation (F = 17.5; p = 0.000) and sig-
nificantly less time to maximum angular dis-
placement for knee flexion (F = 4.7; p = 0.038) compared with the male subjects.

There were no significant differences found
between groups for the vertical ground reac-
tion force variables for either single-leg land-
ing (females, 32.2 ± 5.4; males, 30.4 ± 5.5;
F = 0.75; p = 0.39) or for the forward hop
landing tasks (females, 28.8 ± 5.1; males,
28.4 ± 5.5; F = 0.04; p = 0.84).

For the isokinetic strength assessment
(Table 2), females had significantly lower
peak torque to body weight for knee extension
(F = 7.55; p = 0.011) and flexion (F = 4.52;
p = 0.043).

DISCUSSION
For both landing tasks, the results of the cur-
rent study indicate that females have signifi-
cantly less knee flexion and lower leg internal

<table>
<thead>
<tr>
<th>Kinematic Variables</th>
<th>Hip Flexion</th>
<th>Hip Abduction</th>
<th>Hip Rotation</th>
<th>Knee Flexion</th>
<th>Lower Leg Rotation</th>
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<tbody>
<tr>
<td>Single-leg land</td>
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<tr>
<td>Maximum angular</td>
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<td>displacement</td>
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<tr>
<td>Females</td>
<td>7.12 ± 5.57</td>
<td>−10.67 ± 8.85</td>
<td>7.49 ± 3.69</td>
<td>−17.41 ± 12.96*</td>
<td>3.81 ± 3.42*</td>
</tr>
<tr>
<td>Males</td>
<td>6.65 ± 4.31</td>
<td>−6.09 ± 3.83</td>
<td>3.05 ± 2.16</td>
<td>−31.10 ± 9.92</td>
<td>11.73 ± 8.39</td>
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<tr>
<td>Time to maximum</td>
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<td>angular displacement</td>
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<td>(ms)</td>
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<tr>
<td>Females</td>
<td>126.04 ± 57.39</td>
<td>136.24 ± 52.82</td>
<td>150.17 ± 52.62</td>
<td>130.04 ± 71.8</td>
<td>174.32 ± 41.71*</td>
</tr>
<tr>
<td>Males</td>
<td>140.62 ± 62.86</td>
<td>147.84 ± 37.79</td>
<td>110.21 ± 66.65</td>
<td>187.00 ± 43.98</td>
<td>111.64 ± 33.54</td>
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<tr>
<td>Forward hop maximum</td>
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<td>angular displacement</td>
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<td>(degrees)</td>
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<tr>
<td>Females</td>
<td>4.75 ± 3.3</td>
<td>−9.79 ± 8.41</td>
<td>4.96 ± 3.21</td>
<td>−18.95 ± 13.82*</td>
<td>4.23 ± 3.77*</td>
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<td>Males</td>
<td>5.43 ± 5.79</td>
<td>−8.21 ± 3.7</td>
<td>3.09 ± 2.27</td>
<td>−30.35 ± 9.73</td>
<td>11.86 ± 9.04</td>
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<tr>
<td>Time to maximum</td>
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<td>angular displacement</td>
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<td>(ms)</td>
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<tr>
<td>Females</td>
<td>102.22 ± 51.45</td>
<td>137.13 ± 43.91</td>
<td>124.05 ± 40.57*</td>
<td>130.49 ± 70.37*</td>
<td>84.85 ± 42.19</td>
</tr>
<tr>
<td>Males</td>
<td>95 ± 68.54</td>
<td>155.62 ± 39.23</td>
<td>64.15 ± 37.83</td>
<td>178.73 ± 49.42</td>
<td>99.27 ± 40.29</td>
</tr>
</tbody>
</table>

*Denotes statistical significance at p < 0.05
rotation after impact than males. The results also revealed that females took significantly less time to reach maximum knee flexion subsequently to impact. Because females had less maximum angular displacement than males, it did not take as long to reach their maximum knee flexion angle resulting in a more abrupt absorption of the impact forces of landing (Figs 3,4).

The kinematic pattern of the females in relation to the males during these landing tasks included more hip internal rotation with lower leg external rotation from impact to the maximum rotation point of the maneuver with knee flexion relatively limited. The kinematics during landing of the females in the current study were consistent with those often observed in the noncontact anterior cruciate ligament injury.3,16 The relative lack of knee flexion, combined with a tibial rotary force, muscle reflex, or a combination of both in response to an unexpected perturbation may result in injury to the anterior cruciate ligament.4,9,14,28,30,32,34

The current results are consistent with results from other studies which showed there were gender differences when doing athletic maneuvers, such as cutting4,19 and landing from a jump.13 These studies showed that females tend to land with the knee in a more extended position4,19 and therefore subject themselves to higher forces per body weight during the impact of landing.13 Some reports attribute landing characteristics to training experience of the athlete.2,8,21,24,27,31 In general, skilled, well-trained, or experienced athletes have been reported to have increased ankle plantar flexion,21,24 knee flexion,8,24,31 and lowered vertical ground reaction forces during landing.27,31 Thus this theoretically would permit more time to distribute the impact forces and allow the opportunity for the musculature to absorb these forces.24,31 However, to date, no studies have investigated a potential relationship of gender by skill level for these landing characteristics.

**Fig 3.** Points A and B represent the maximum angular displacement of knee flexion and the time to achieve this position after ground contact. The deficit represents a significant (p < 0.05) difference in knee position after ground contact between females and males.

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**TABLE 2.** Isokinetic Assessment: Peak Torque to Body Weight (N-m) at 60°/Second

<table>
<thead>
<tr>
<th>Group</th>
<th>Quadriceps</th>
<th>Hamstrings</th>
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<tbody>
<tr>
<td>Females</td>
<td>222.93 ± 30.86*</td>
<td>113.74 ± 23.66*</td>
</tr>
<tr>
<td>Males</td>
<td>271.68 ± 59.27</td>
<td>131.72 ± 21.89</td>
</tr>
</tbody>
</table>

*Denotes statistical significance at p < 0.05
The other significant result of the current study is related to the relative weakness of the female quadriceps and hamstrings when normalized to body mass compared with the males (Fig 5). This finding may play a fundamental role in the landing position observed in the females during landing.

The role of the quadriceps landing seems to be critical to the distribution and absorption of the impact forces resulting from landing. Although the vertical ground reaction forces did not differ between genders in the current study, the relative lack of knee flexion subsequent to impact in females has significant implications.

**Fig 4.** Points A and B represent the maximum angular displacement of knee flexion and the time to achieve this position after ground contact. The deficit represents a significant \( p < 0.05 \) difference in knee position after ground contact between females and males.

**Fig 5.** The quadriceps isokinetic peak torque to body mass at 60°/second for the male group was significantly greater \( p < 0.05 \) than that of the female group. The hamstring isokinetic peak torque to body mass at 60°/second for the male group was significantly greater \( p < 0.05 \) than that of the female group.
for the manner in which force transmission up the kinetic chain occurs. The authors suspect that the lack of vertical ground reaction force difference was attributed to other force absorbing compensatory mechanisms that were not studied, such as ankle kinematics or muscle activity.

Subsequent to impact, the quadriceps muscle eccentrically contracts to control knee flexion and decelerate the land. The minimal knee flexion at impact observed and the lack of controlled knee flexion deceleration in the female athletes may be related to the relatively weak leg musculature, especially the quadriceps. Without sufficient strength available to decelerate the body by the eccentric quadriceps mechanism, it seems that the females land in a more extended knee position and tend to maintain this extended position subsequent to ground contact rather than absorbing the impact with controlled knee flexion. This knee extended position, combined with internal hip rotation, makes females vulnerable for anterior cruciate ligament loading.

Physicians, athletic trainers, and others who are concerned with the care of athletes, need to evaluate the biomechanics of the female athletes to ensure proper technique is being used during landing activities and continue to educate coaches to implement training practices using proper techniques. Maximizing joint angles, specifically knee flexion, subsequent to impact will aid in attenuating potentially harmful forces and ensure protective biomechanical patterns, which may promote more appropriate muscle firing patterns to protect the knee. Additionally, awkward or poor landing skills may identify a specific muscle weakness. Additional research is needed to explore if a relationship exists between the weakness of muscles and poor landing tasks as center of gravity and trunk angle differences may alter hip and knee stability.

The data from this study suggest that biomechanical and neuromuscular variables differ between genders during impact on landing. Males had a greater amount of knee flexion subsequent to impact. The larger flexion displacement serves to attenuate impact forces reducing loads imposed on the joint. The absence of this controlled knee flexion in females may be related to the weaker quadriceps and hamstrings, resulting in an abrupt stiffening of the knee. These factors need to be considered related to the pathoetiology of anterior cruciate ligament injuries in the female athlete.

References


