Strategies for Enhancing Proprioception and Neuromuscular Control of the Knee

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Proprioception and neuromuscular control of the knee are compromised after ligament injury and must be regained if the athlete is to return to high level sports at a normal injury risk level. The anterior cruciate ligament deficient and reconstructed knee will be used as a model to describe differences in proprioception and neuromuscular control to those of an uninjured knee. The purpose of the current review is threefold. First, the basic science of proprioception and neuromuscular control specific to the knee will be summarized and reviewed. The review will include an overview of terminology, neurophysiology, and the effects of injury on the function of both lower limbs. Second, tools used for assessment and rehabilitation of proprioceptive deficits will be evaluated. Specific rehabilitation procedures that incorporate prophylactic conditioning that focus on transitioning the injured athlete back into sport will be presented. Finally, the literature with respect to gender variation in proprioception and neuromuscular control will be evaluated. The goal of the current review is to provide the clinician and the clinical scientist with sufficient background information for the development of quantitative methods to evaluate a patient’s functional capacity and to assist in preventative, preoperative, and postoperative decision-making strategies.

Basic Science of Proprioception and Neuromuscular Control of the Knee

Defining Proprioception:
The task of defining proprioception is one that has been attempted previously and has created controversy in the scientific community. Initially, definitions such as “the ability to receive input from muscles, tendons and joints and process information in a meaningful way in the central nervous system,” and “assists in the knowledge of where a limb is in space,” prevailed in the literature. Controversy continues to prevail because a universally accepted definition remains to be formulated. This inability to generate an acceptable, all-encompassing definition on the terms proprioception and neuromuscular control, show the complexity of the topic and the difficulty in proceeding with valid and reliable research.

Sherrington first described proprioception in 1906 in his classic contribution to the literature regarding nervous system function. Difficulty in the direct interpretation of his writing has led to significant confusion in the scientific community. However, for the current review, a working definition of proprioception based on a paraphrase of Sherrington’s
early work will be used as the standard definition. Sherrington defined proprioception as the culmination of all neural inputs originating from joints, tendons, muscles, and associated deep tissue proprioceptors. These inputs are projected to the central nervous system for processing and ultimately result in the regulation of reflexes and motor control. This definition views proprioception primarily as a sensory activity, occurring along the afferent pathway. More recently, the definition of the proprioceptive system has been expanded to include the complex interaction between the sensory pathways and the motor pathway (efferent system). This system has come to be known as the sensorimotor system.33

**Neurophysiology of Proprioception and Neuromuscular Control of the Joint**

When a proprioceptive stimulus is presented to the body, input occurs at three separate locations, including the visual system, the vestibular system, and the peripheral mechanoreceptors (Fig 1). These peripheral mechanoreceptors are

![Flow chart of lower limb dynamic neuromuscular response to sensory receptor input](image)

**Fig 1.** A flow chart of lower limb dynamic neuromuscular response to sensory receptor input is shown.

**Sensory Receptors**

- mechano-receptor
- visual
- vestibular

**Proprioceptive Control**

- reflexes (fastest)
- brain stem (intermediate)
- cerebellum (slowest)

**Dynamic Neuromuscular Response**

**Inappropriate**

**Appropriate**
located in various locations throughout the body including skin, joints, ligaments, tendons, and muscles. The role of the mechanoreceptors is that of a “transducer to convert mechanical energy of a new action potential.”3 Basically, the mechanoreceptor is a specialized nerve plexus serving a mechanical role to provide position sense and conscious awareness by initiating reflexes to stabilize joints and avoid injury. Previous studies all substantiate the role of mechanoreceptors in various joint structures as acceptors of information from the environment for processing by the central nervous system.28,29,47,48

After the acceptance of the input, the message then is transferred to the central nervous system and is processed at one of three levels. Reaction at the spinal level is a reflex response. This represents a fast response that is necessary for protective reflexive joint stabilization. This also helps mediate movement from higher levels of the central nervous system. The second level of motor control is via the lower brain (basal ganglia, brainstem, and cerebellum). This area acts as a way station for command from higher levels. It also is involved in the timing of motor activities, learning of planned movements, and control of complex movement patterns of a sustained and repetitive nature. Finally, processing can occur at the cerebral level, where there is control of voluntary movement. After the processing of information a motor response occurs. This represents the slowest neural response because of the presence of multiple synapses and increased distance of impulse propagation.34

The anterior cruciate ligament deficient knee provides clinical researchers with an excellent model to study neural signaling and proprioceptive deficits in the knee. Currently, it is well-established that injury to the anterior cruciate ligament results in mechanical instability of the knee.15,17,20,41,42,49 Deficiency of the anterior cruciate ligament often is associated with giving-way in patients returning to activities requiring cutting, twisting, acceleration and deceleration maneuvers, often despite rehabilitation after injury, rendering them functionally unstable.15,41,42,49 The rule of thirds suggests that ¼ of all patients with anterior cruciate ligament deficiency are unable to return to activities of daily living because of instability, ¼ can function with recurrent instability during activities of daily living but cannot resume sports activities, and the final ¼ can resume sports activities without experiencing recurrent instability.42 Snyder-Mackler et al53 also have shown a lack of correlation between anterior cruciate ligament insufficiency and functional instability in a select group of athletes. They describe patients with increased joint laxity and functional stability as copers and patients with increased joint laxity and functional instability as non-copers. Surgeons often recommend anterior cruciate ligament reconstruction to patients who desire to return to high levels of activity. However, even after static mechanical stability is restored surgically through anterior cruciate ligament reconstruction, the patient may continue to experience functional instability (giving-way episodes or perceived instability) during dynamic activity. These findings show the complex nature of joint stability.4,19,43

Several authors have studied the hypothesis that mechanical stability does not guarantee functional stability, and have suggested evidence that the anterior cruciate ligament has a sensory and proprioceptive function, in addition to its role as a static stabilizer.28,29,47,48 Anatomic and histologic studies have shown a rich neurologic innervation and the presence of specific proprioceptive mechanoreceptors in the fibers of the anterior cruciate ligament.16,28,29,47,48 These studies have helped validate the presence of proprioceptive mechanoreceptors and show their role in the afferent pathways of the sensorimotor system. A study by Pitman et al44 measured somatosensory evoked potential recordings in the cerebral cortex after stimulation of the anterior cruciate ligament. They found evidence of proprioceptive receptors within the fibers of the intact anterior cruciate ligament in humans and the presence of cerebral activity after stimulation, validating the successful transmission of this message. Finally, other studies
have explored the modulation of muscle activity after stress is placed on the anterior cruciate ligament. These authors reported that coincident with forced increases in anterior tibial translation, muscle responses were observed. Specifically, increases in hamstring activation and inhibition of quadriceps activity were reported. Therefore, a motor response to a proprioceptive stimulus and a complete sensorimotor loop is complete via the sensorimotor system.

Assessment of Proprioceptive and Neuromuscular Control of the Knee

Various methods have been developed to attempt to assess the proprioceptive and neuromuscular control of the joint. Assessment of joint position sense was one of the first methods used to determine a patient’s proprioceptive aptitude. This method involves the setting of the limb at a certain, predetermined angle and then asking the subject to reproduce the angle, measuring the deviation from the previous angle. Although this is an easy test to execute clinically, it has been criticized for its high measurement variability and inherent lack of reliability. In addition, it only analyzes a portion of proprioception, joint position sense, and fails to take into account joint kinesthesia. A second method that is used to assess proprioception is threshold to perception of passive movement. This testing method evaluates the patient’s ability to detect movement in the limb. The patient’s limb is placed at a certain angle and the patient is blinded to its location. The limb then is moved passively at a very slow speed, typically, 0.5° per second. The subject is asked to tell the tester when motion in the limb is first detected and the measurement of distance traveled between the time motion started to the time motion was detected by the subject then is recorded. This has been found to be a fairly reliable assessment tool for measuring proprioception, however, it fails to assess any characteristics of joint position sense, because it solely assesses kinesthetic awareness.

A third method to assess proprioception and neuromuscular control includes the measurement of muscle activation and latency of muscular reflexes after a stimulus. This method has been used frequently in the study of the patient with anterior cruciate ligament deficiency. Anterior tibial translation force is applied and reactive hamstring latency is measured. Finally, the use of balance assessment and stabilometry can be used to assess postural control and inferences can be made to proprioceptive capabilities and neuromuscular control. The need to assess proprioceptive ability and neuromuscular control accurately is widely accepted in the scientific community; however, there is great disagreement to the most appropriate and accurate means of accomplishing that task. Beynon et al summarized it well with their conclusion that “the importance of proprioception as a clinical outcome measure is well recognized, but the best measurement technique has yet to be determined.”

Proprioceptive Deficits in the Patient with an Anterior Cruciate Ligament Deficiency

Deficits in conscious, voluntary knee kinesthesia and proprioception after anterior cruciate ligament rupture have been reported in several studies. Independently, these authors studied the proprioceptive capacity of subjects with anterior cruciate ligament deficiency. The methodology varied significantly among these studies with respect to the means of proprioceptive assessment, ranging from active and passive repositioning to threshold to detection of passive movement. For example, Barrack et al studied the threshold for detection of passive motion in 11 athletes with anterior cruciate ligament deficiencies. They found a significantly higher mean threshold value that was indicative of a proprioceptive deficit. Wojtys and Huston studied muscle timing and recruitment after forced anterior tibial translation in athletes with anterior cruciate ligament deficiency. These authors found significant changes in muscle timing and recruitment after anterior cruciate ligament rupture. These studies were able to incorporate assessment, not only of the afferent pathway, but also the efferent response, and to achieve a...
more complete examination of the sensorimotor system. Although the methodology varied, the results of these studies consistently showed proprioceptive deficits in the subjects with anterior cruciate ligament deficiency.

Timing of Proprioceptive Return After Anterior Cruciate Ligament Reconstruction

The return of proprioceptive function after anterior cruciate ligament reconstruction has been reported.4,13,19 Studies by Co et al13 and Harrison et al19 evaluated the proprioceptive ability of patients with anterior cruciate ligament reconstructed knees. Independently, these authors concluded that the proprioceptive ability of the reconstructed knee was equal to that of controls. Co et al13 assessed proprioception through the use of reproduction of passive motion, relative reproduction of joint position, and threshold to detection of passive motion, in addition to measuring the vertical component of heel strike force during gait. Harrison et al19 measured proprioception through the use of single leg stance and postural sway and concluded that anterior cruciate ligament reconstructed knees were equal to controls. Barrett4 showed that functional outcome was highly correlated with proprioceptive measures in the patient who had anterior cruciate ligament reconstruction. Conversely, a study by MacDonald et al15 using threshold to perception of passive motion, found no improvement in proprioceptive function after the reconstruction. Therefore, controversy exists regarding the timing and return of proprioceptive function of the anterior cruciate ligament reconstruction.

From a clinical standpoint, attempts to assess functional stability often are inconclusive. After anterior cruciate ligament reconstruction and restoration of mechanical stability, the goal is to maximize functional stability and return the patient to his or her preinjury level of activity. Return of a patient to high level sports before functional stability has been achieved may lead to a new injury or failure of the reconstruction. No reliable method for the objective determination of functional stability of the lower extremity currently is available. The decision to return the patient to unrestricted activity usually is based on a combination of muscle strength measurements, functional tests, and time from surgery. Use of quadriceps and hamstring strength measurements alone as criteria for return to sports has been shown to be an inadequate assessment, because patients can have functional instability even when strength has returned.32,39 In addition, it has been reported that commonly used functional performance tests using one-legged hopping and jumping maneuvers have low sensitivity for detecting functional limitations.2 In separate studies, Tegner et al13 and Barber et al2 found that an unacceptably high proportion of patients whose knees were functionally unstable had normal limb symmetry scores on one-legged hop tests. Noyes et al19 reported that only 50% of patients with anterior cruciate ligament deficiency had abnormal limb symmetry on a single-leg hop test and 62% had abnormal limb symmetry on two tests. Lephart et al32 reported on three functional performance tests designed to predict functional recovery (carioca maneuver, shuttle run, and cocontraction semicircular maneuver). The mean functional score differences between patients with an anterior cruciate ligament deficiency and healthy subjects were significantly different, however, the variability among the patients with instability was large enough to categorize a significant percentage of the patients with anterior cruciate ligament deficiency as being healthy.32 Therefore, the criteria currently used to return patients to full function may not accurately assess their functional stability and their ability to return to their highest functional level.

Co et al13 studied 10 subjects with anterior cruciate ligament reconstruction at an average of 32 months postoperative to assess proprioception and neuromuscular control status after anterior cruciate ligament reconstruction. They used three joint proprioception tests that in-
cluded reproduction of passive motion, relative reproduction, and threshold to detection of passive motion. They found the anterior cruciate ligament reconstructed limb to be essentially equal to the contralateral limb and a control group in proprioceptive function. Harrison et al\textsuperscript{19} examined 17 patients with anterior cruciate ligament reconstruction and compared them with a control group. Patients were 10 to 18 months postoperatively. Functional stability was determined through subjective scoring by two physical therapists during single-leg stance with the patient’s eyes open and closed. Postural sway was measured on a force plate. The authors found no significant difference in balance measures between involved and noninvolved limbs; however, the authors stated that the usefulness of single-leg standing balance for anterior cruciate ligament reconstructed knees at 10 to 18 months postoperatively is questionable because of the patient being too functionally advanced for these measurements to detect variation between limbs. The studies by Co et al\textsuperscript{13} and Harrison et al\textsuperscript{19} show no significant difference between the anterior cruciate ligament reconstructed knee and the noninvolved limb. However, the subjects were studied at a minimum of 10 months postoperatively.

Patients with anterior cruciate ligament reconstruction have significant deficits in single-leg balance at 6 months and greater postoperatively.\textsuperscript{24} At 6 months postoperative, the patient with anterior cruciate ligament reconstruction continues to have significant proprioceptive deficits (Fig 2). This finding is important when considering aggressive anterior cruciate ligament rehabilitation protocols, which advocate return to twisting and rotational sports as early as 3 to 4 months postoperatively.\textsuperscript{30} If proprioceptive deficits continue to exist at this point, regardless of strength and range of motion (ROM), clinicians may be subjecting their athletes to a high risk of graft failure or reinjury.

**Bilaterality of Proprioceptive Deficits**

Significant postural balance deficits may exist in the involved and uninvolved limb of patients with anterior cruciate ligament deficiency. Hewett et al\textsuperscript{24} reported that the primary single-leg balance abnormality was in the sagittal plane in these patients. In addition, similar deficits were present in the involved and uninvolved limb. This deficit persisted in the involved limb up to 1 year postoperatively (Fig 3). This finding of balance deficits in the involved limb after anterior cruciate ligament injury and after anterior cruciate ligament reconstruction is not unique. Other studies have suggested similar findings of proprioceptive

![Fig 2. The mean postural instability in the anterior cruciate ligament (ACL)-deficient limb of subjects preoperative and 3, 6, 9, and 12 months postoperative compared with age and gender-matched control subjects is shown.](image1)

![Fig 3. The mean postural instability in the noninvolved contralateral limb of subjects with anterior cruciate ligament (ACL) deficiency preoperative and 3, 6, 9, and 12 months postoperative compared with age and gender-matched control subjects is shown.](image2)
deficits in the anterior cruciate ligament deficient knee.3–5,14,16,38,60

Proprioceptive deficits also have been well documented in the noninvolved limb. Corrigan et al14 found proprioceptive deficits in both limbs of athletes with unilateral anterior cruciate ligament deficiency. Their study used threshold to perception of passive motion and position sense to assess proprioception in the subjects. Friden et al16 also examined patients with unilateral anterior cruciate ligament deficiency and found increased postural sway in the frontal plane in both lower extremities. Wojtys and Huston60 found deficits in lower extremity muscle timing and recruitment order bilaterally when assessing patients with anterior cruciate ligament deficiency. The results of Hewett et al24 are consistent with these findings and raise an interesting question regarding use of the contralateral limb as a control during proprioceptive testing. These results indicate that clinicians should not use the contralateral limb as a control when assessing proprioceptive parameters, because deficits similar to the involved limb are seen on the noninvolved side.

Stabilometry as a Measure of Proprioception in the Anterior Cruciate Ligament Deficient Knee

Several studies have explored the use of postural balance deficits as a means of assessing a patient’s functional stability.16,24 Postural balance is a complex function that relies on the interplay of several factors, including proprioception, dynamic joint restraints, static joint restraints, and postural equilibrium. Dynamic joint restraints are muscle-tendon units that maintain limb and joint position and react to changing loads and forces. Static joint restraints include ligaments and bony architecture that limit joint motion. Postural equilibrium refers to higher level functions including visual and vestibular input. Stabilometry is an objective and quantitative method for evaluating postural balance.16,19,38,57,59 In the past, stabilometry studies were done on a static force plate with measurement of body sway in the sagittal plane, coronal plane, or both.16 More recently, mobile platforms that measure body sway in two dimensions about a center of pressure have been developed.24

Stabilometry first was used in orthopaedic research to study instability of the ankle. Tropp et al58 showed that stabilometric measures correlated with functional stability of the ankle, but not mechanical stability. In addition, these authors were able to show that an abnormal stabilometric score was predictive of future ankle injury.57–59 Several authors have shown deficits in stabilometric score for anterior cruciate deficient knees as compared with controls.19,38,61 Mizuta et al18 compared stable and unstable cruciate deficient knees with a control group and found that the unstable group had significant stabilometric deficits relative to the other two groups. They concluded that stabilometry was a useful tool for assessment of subjective functional knee stability.

Gender Differences in Proprioception

A deficit exists in the knowledge base functional stability with respect to gender. Few studies have examined neuromuscular control differences between males and females.23,27 Previous studies have shown that women participating in jumping and cutting sports have a fourfold to sixfold higher incidence of knee injury than males.1,27,62 One possibility for these differences with respect to knee injuries may be attributable to deficits in proprioception and neuromuscular control in female athletes.24 Two previous studies by Black et al18 and Hellenbrandt and Braun22 have explored postural sway in healthy subjects and found no differences between genders. Both of these studies tested subjects on stable force platforms. Differences between gender in postural sway on a dynamic platform have not been reported previously. Therefore, an unknown relationship between neuromuscular control and gender exists and needs additional assessment.

Gender Differences in Single-Leg Stability

Hewett et al24 examined single-leg stability of male control subjects compared with female control subjects and reported that the female subjects had significantly more stability than
males on the involved and noninvolved knee (Fig 4). However, in the subjects with an anterior cruciate ligament deficiency, the males had significantly more stability than the females preoperatively on the involved and noninvolved limb.24

In postoperative examination, the males continued to have greater total stability than females with significant differences remaining between these groups at 6 months, at 9 months, and at 12 months postoperative (Fig 4). The males’ instability on the involved limb peaked at 3 months postoperative, whereas the females had the most instability at 6 months postoperative.24

The finding of proprioceptive differences between genders raises important issues. First, females with intact knees have greater single-leg balance than males with intact knees. This difference is presumed to be attributable to the lower center of gravity in female control subjects.30 However, after injury to the anterior cruciate ligament, females seem to experience greater deficits in balance than males. In addition, the return of single-leg balance after anterior cruciate ligament reconstruction is slower in females than males. Females have significantly greater deficits in single-leg balance than males after anterior cruciate ligament rupture and may need more time to recover from anterior cruciate ligament reconstruction to regain functional stability and be prepared to return to a maximum level of function. Therefore, researchers should group single-leg stability data by gender and analyze the groups separately. These findings also indicate that the clinician needs to stress proprioception exercises earlier in the rehabilitation for the female patients to aid in a faster return of proprioceptive abilities.

An important question to consider is whether female subjects with anterior cruciate ligament rupture possess deficits in balance or postural control before injury, which creates a predisposition to injury or the alternative possibility, that anterior cruciate ligament injury is more traumatic to the proprioceptive systems of females than males.24 If the anterior cruciate ligament injury in females results in greater proprioceptive damage, anterior cruciate ligament injury may be significantly more traumatic to women and these increased deficits need to be addressed in the postoperative course of rehabilitation. The possibility that females with postural sway deficits possess a greater propensity to knee injury suggests the need for prescreening for single-leg balance before athletic participation to assess for injury risk.

Proprioceptive and Neuromuscular Control Deficits in the Female Athletes

The alarmingly high incidence of females presenting with noncontact knee injuries caused by jumping and cutting sports coupled with the geometric growth in female participation in these high risk sports has significantly increased the gender gap in the incidence of noncontact knee injury. Hewett et al23 observed three neuromuscular imbalances, which were termed dynamic neuromuscular imbalance. The first imbalance is the tendency for females to be ligament-dominant. Ligament dominance refers to the absence of muscle control of mediolateral knee motion that results in high valgus knee torques and high ground reaction forces. Typically during single-leg landing, pivoting or deceleration, as often occurs during knee ligament injury, the female athlete allows the ground reaction force to control the direction of motion of the lower extremity joints, and the ligament
to take on a significant percentage of the force. This lack of dynamic muscular control of the joint leads to high forces and high valgus torques at the knee (Fig 5). The second imbalance is termed quadriceps dominance. With quadriceps dominance, female athletes activate their knee extensors preferentially over their knee flexors during sports movements to stabilize their knee, which accentuates and perpetuates strength and recruitment imbalances between these muscles. This cycle of quadriceps dominance should be addressed and overcome with dynamic neuromuscular training. The third imbalance is dominant leg dominance. Dominant leg dominance is the imbalance between muscular strength and recruitment on opposite limbs, with the nondominant limb often having weaker and less coordinated hamstring musculature. During single-leg landing, pivoting or deceleration, the female athlete may have a lack of dynamic muscular control of the nondominant knee, which may predispose the knee to injury.

The enhancement of neuromuscular balance is an important concept for the development of any neuromuscular training program. Enhancement of balance is important in every plane: the coronal, the sagittal, and the transverse. The neuromuscular control problem in females basically is an imbalance of three important neuromuscular parameters. With ligament dominance, there exists an imbalance between the neuromuscular and ligamentous control of the joint. With quadriceps dominance, there is an imbalance between quadriceps and knee flexor strength and coordination. With dominant leg dominance, there is an imbalance between the two lower extremities in strength and coordination. Therefore, an important neuromuscular reeducation concept is that the trainer or therapist must create balance in each of these parameters. The neuromuscular training program, which was developed to achieve this goal, will be detailed in the following section.

Clinical Use of Strategies for Improving Proprioception and Neuromuscular Control of The Knee: Injury Prevention and Preoperative and Postoperative Planning Potential for Preparticipation Screening

The assessment of potential injury risk before sports participation followed by intervention may decrease the relative injury incidence in
The three muscular imbalances detailed previously give a framework for preparticipation screening of female athletes that serve as a model for any population prone to injury to the anterior cruciate ligament. Preparticipation screening of athletes may be used to identify those athletes predisposed to knee injury and those who would benefit from a training program to enhance strength, proprioception, and neuromuscular stabilization of the knee. Force plates, optoelectronic digitizing cameras, and dynamometers used by biomedical researchers are not readily accessible to athletic trainers and coaches. Simple methods to determine which athletes are at increased risk of injury, which are readily available to coaches, trainers, and athletes might allow for large scale screening for injury-prone athletes and clearly identify those athletes who need preparticipation training. The knowledge gained from methodologies such as these could have a major impact on how female athletes prepare for sports participation.

McKeag reported that 10% to 12% of adolescent athletes have deficiencies during preparticipation testing that may preclude them from participation; these deficiencies include side-to-side strength imbalances, flexibility imbalances, and inadequate conditioning or skill level. Smith and Laskowski reported that 4% of athletes have musculoskeletal deficits that either preclude them from playing or require referral for additional evaluation. With the ever-increasing popularity of sports such as soccer, volleyball, basketball, and softball and the rapidly increasing number of participants each year, even higher numbers of injuries could be avoided in the future. To participate in high-risk jumping and cutting sports, athletes may need to be evaluated and show proficiency in strength, flexibility, and advanced motor skills tests. Without testing and deficit correction, the increased risk of serious knee injury in female athletes may maintain its pattern of geometric growth.

**Prophylactic Neuromuscular Training for Injury Prevention**

Chandy and Grana found that significantly more female than male high school athletes had knee injuries that required surgery and suggested, “emphasis be placed on functional evaluation and conditioning of the quadriceps and hamstring muscles to prevent these injuries.” Beck and Wildermuth stated that noncontact anterior cruciate ligament injuries are “due to coordination failure” and involve “a combination of high velocity and momentary loss of normal protective muscle support.” Training has been shown to increase active knee stabilization in the laboratory and decrease the incidence of serious knee injury, including anterior cruciate ligament injury, on the court or field in an athletic population. Training and strength differences may account for only part of the increased incidence of knee injury in female athletes, but lowering these high figures by even a percentage could have a significant effect on the number of knee injuries in female athletes.

Caraffa et al showed in a prospective controlled study that neuromuscular training of high level male soccer players significantly decreased the incidence of anterior cruciate ligament injury. After a progressive five-phase training program on balance boards, injury incidence decreased more than sevenfold in these male athletes. Hewett et al reported a plyometric and strength training program that decreased peak landing forces and valgus and varus torques at the knee (Fig 6). These authors also showed a marked imbalance between hamstrings and quadriceps strength in female athletes before training. In addition, males had knee flexor moments during landing from a jump, which were three times higher than females. The training program significantly increased hamstrings power and strength, increased hamstrings to quadriceps peak torque ratios and decreased right to left leg imbalances in hamstrings strength. This program also was tested to determine whether it has a significant effect on injury rates in athletes during competition. Female athletes trained with the program were three to four times less likely to suffer serious knee injuries. The results observed with this program justify the alteration of current protocols for preparing females for participation in high-risk sports.
training, if effectively implemented on a widespread basis, could help to significantly decrease the number of athletes injured each year.

Hewett et al. reported the first prospective study of the effects of neuromuscular training (using a plyometric training program) on knee injury in the high-risk female sports population. The rate of serious knee injury was 0.43 in untrained females, 0.12 in trained females, and 0.09 in males (injuries per 1000 exposures). Chi square analysis indicated a significant effect of training on group injury rates (Fig 7). Untrained females had a significantly higher incidence of serious knee injury than trained females and males. Trained females were not different than untrained males. Training resulted in even greater differences in noncontact injuries be-

**Fig 6A–C.** A serial progression of a squat jump maneuver is shown, from (A) squat to (B) spring to (C) jump.

**Fig 7.** The relative injury per 1000 player exposures in untrained female athletes, trained female athletes, and untrained male athletes is shown.
tween the female groups. This prospective study showed a decreased incidence of serious knee injury after neuromuscular training in the high-risk female sports population.

**Clinical Relevance of Preoperative and Postoperative Proprioceptive Deficits**

Proprioceptive and neuromuscular control deficits exist after anterior cruciate ligament rupture and well into the postoperative rehabilitation period. Clinicians should be aware of these deficits and focus rehabilitative interventions in these areas. Through the assessment of postural balance, Mizuta et al.\(^3\) compared subjective complaints of functional instability with a stabilometric measurement on a force plate and found an impaired standing balance in the functionally unstable group. They concluded stabilometry was a useful method for evaluating functional instability of the knee. However, Mizuta et al.\(^3\) used a stable force plate for stability measures rather than a stabilometry system with an unstable platform. Balance assessments are general measures of inputs from multiple variables. Even when experimental protocols attempt to eliminate certain variables such as audio and visual input, testing measures usually are unable to indicate specifically which variables are abnormal.

Preoperative single-leg stability of subjects with anterior cruciate ligament deficiency can show a significant deficit of the involved limb and the noninvolved limb when compared with the control group.\(^2\)\(^4\) This significant deficit in both limbs persisted at 3, 6, and 9 months postoperative (Fig 2). The mean values for the single-leg stability at 12 months postoperative showed significant deficits in the noninvolved limb; however, no significant difference was seen in the involved limb. In addition, when total stability of the subjects’ involved limb versus the noninvolved limb was compared, no significant difference was seen preoperatively.

**Rehabilitation for Regaining Proprioception After Injury and Surgery**

Protocols for the anterior cruciate ligament deficient and reconstructed knee have been developed and previously described in detail.\(^2\)\(^1\) Immediate motion and early, protected weight-bearing now are standard protocols. Rehabilitation programs should be evaluated based and tailored within the limits of the individual patient. Patients should reach full ROM and weightbearing by 5 to 6 weeks. A running program should be started at approximately 3 to 4 months with a functional program including cutting and pivoting initiated at 5 to 6 months. Return to high-risk sports should occur between 6 to 9 months.

In the past several years, rehabilitation protocols were published that attempted to outline the fastest and most aggressive means to rehabilitate the patient after anterior cruciate ligament reconstruction.\(^5\)\(^2\)\(^1\)\(^5\)\(^0\) When exploring the current literature regarding rehabilitation after an anterior cruciate ligament reconstruction, there is significant controversy regarding the safest and most efficient means to rehabilitate these patients. Because immediate motion was advocated after intraarticular anterior cruciate ligament reconstruction, clinicians have pushed to accelerate rehabilitation after anterior cruciate ligament reconstruction in an attempt to advance the patient to return to sports as quickly as possible.\(^5\)\(^0\)

Rehabilitation after anterior cruciate ligament reconstruction is a multifaceted task. Protocols for rehabilitation have been developed based on scientific data and clinical experience, which provides the patient the opportunity to return to sports in a rapid time frame without compromising the safety of the patient. Focus should be placed on decreasing the risk of long-term complications such as graft failure or laxity, patellofemoral conversion, and loss of motion while considering patient goals and concomitant injury. Therefore, different protocols after anterior cruciate ligament reconstruction have been developed, accelerated and delayed, and patients can be placed into specific groups after surgery. Patients are candidates for accelerated programs unless they possess a complex avascular meniscus repair, concomitant alternate ligament reconstruction, concomitant patellofemoral realignment procedures, and significant articular cartilage lesions or had revision surgery. These patients are pro-
gressed by the guidelines of a delayed protocol. A detailed description of these rehabilitation protocols is beyond the scope of the current review; however, the progression of the proprioceptive and neuromuscular control components of one current anterior cruciate ligament protocol will be reviewed.21

Training of the proprioceptive and neuromuscular control systems should begin early in the rehabilitation process. In the first week of Phase I of rehabilitation, simple weight shifting can initiate this process. Weight shifting acts as a lead into the initiation of a weight-bearing program. Progression to weightbearing can be taught with the aid of a bathroom scale. The patient should be taught to feel the progression of weight from 25% to 100% with the feedback of the scale and then be taught to partial weightbear with crutches.21

Proprioception training continues in the second phase of the program with the initiation of balance board and stabilometry training.21 The initiation of closed kinetic chain activities assists in recruitment of neuromuscular control of the hamstring musculature. Exercises such as wall sits, mini-squats, and lunges help initiate quadriceps and hamstring cocontraction and can be progressed by adding resistance components, using unstable surfaces and adding varus and valgus stress. When the patient is able to bear 100% of his or her body weight safely, progression to single-leg standing activities can be used to additionally challenge the lower extremity musculature and recruit the neuromuscular system for proximal stabilization at the hip. Finally, the patient should be initiated on a cup-walking program. This helps retrain the patient to resume a normal gait pattern by forcing exaggeration of knee and hip flexion during the swing phase of gait, rather than having a rigid knee, which frequently is compensated with hip hiking.21

Phase III incorporates a progression of prior proprioceptive activities to more advanced levels. Activities such as lateral stepping over cups, 90° rotation steps, and single-leg standing activities using resistance in the uninvolved leg with Theraband, all challenge the patient to use their sensorimotor system and compensate for the deficits. Additional challenges to the neuromuscular pathways can be added through balance perturbations and simultaneous activities that require use of the upper extremity while executing activities that require the use of the lower extremity. In addition, upper body plyometric tosses while single-leg standing on the involved limb can challenge the athlete additionally.

Phase IV represents a continued progression of the current proprioceptive activities. Single-leg standing activities are progressed to standing on a trampoline or foam roll. Phase V incorporates not only a progression of current proprioception drills but also the initiation of a straight-line running program if certain baseline criteria with respect to strength and graft integrity, are met. Additional challenges can be made through the addition of backward running and submaximal effort lateral shuffle and cross over drills.

Phase VI represents a progression to more functional, sports-specific activities. Pending the successful initiation of the straight-line running program and attainment of certain baseline criteria, cutting and pivoting activities are initiated. These drills should begin with activities that require less hard cutting, such as figure eight running in a very large area (20 to 30 yards) at submaximal speed. From this point, increasing speed can advance the athlete, decreasing the area of the figure eight and the addition of more advanced cutting activities. More advanced activities include lateral cutting drills, shuttle runs, and pivoting drills. It is crucial at this time to cater the cutting drills to the athlete’s goals and his or her return to sport needs.

Plyometric training also is initiated at this time. Starting with simple hopping drills, such as box hops on a soft surface is a good means to initiate this activity. The athlete then can be advanced to more aggressive jumping drills. The crucial concept with any plyometric program is good technique. This serves as a good introduction to plyometrics and can introduce the concept of technique perfection. More
simple jumping drills serve as a lead in to the more advanced plyometric training.

**Neuromuscular and Proprioceptive Preparation for Return to Sports**

Successful completion of physical therapy during the 4- to 6-month postoperative period places the athlete in a precarious position. This is the point in which they often are released for full activity, especially with the advent of accelerated rehabilitation. At this point, the athlete is prepared to begin functional proprioceptive training in preparation for sport competition, yet is not necessarily ready to begin sports activities. The physical therapist or athletic trainer should attempt to bridge the gap in the athlete’s perceived and actual sports readiness. The patient must understand that although the reconstruction of the ligament may have created a statically stable joint, the athlete may not have a functionally stable knee during dynamic movements. Coordination between active (muscle) and passive (ligament) restraints is required to control tibiofemoral motion and create a dynamically stable knee. The passive mechanical function of the anterior cruciate ligament graft must be complimented with neuromuscular afferent input that increases joint position sense and reflex stabilization of the knee through proper efferent response. A dynamically stable knee is the product of intact soft tissue restraints and an appropriately functioning proprioceptive system. Although the definitions of proprioception may vary, its role in creating a dynamically stable joint and the importance of its development during rehabilitation of the athlete is accepted universally. A progressive, functional rehabilitation program is required to provide the athlete with an effective means for facilitating positive adaptations to the proprioceptive function of the knee. Functional neuromuscular and proprioceptive training should provide the athlete with a dynamically functional joint that is prepared to respond to the extreme forces generated during athletic competition, reducing the risk of reinjury and optimally preparing the athlete to achieve preinjury performance levels.

Functional neuromuscular and proprioceptive training may be defined as movement training progressions that facilitate the development of multijoint neuromuscular engrams that combine joint stabilization, acceleration, deceleration and kinesthesia through intermittent protocols that progress from low intensity movements focused in a single plane to multiplanar power training. Functional neuromuscular and proprioceptive training must incorporate an appropriate balance between developing the proprioceptive abilities of the athlete and exposing the athlete to a contraindicated movement that puts them in pain or at risk of injury. Introduction of this type of training in the rehabilitation program may create acute soreness; however, the trainer should use discretion as to the appropriate intensity and progression of exercises. Proper training progression should take the athlete through a combination of high-risk maneuvers in a controlled situation. This type of proprioceptive stress may aid the development of spinal reflexes that more quickly and effectively stabilize the joint than the voluntary muscular movements that require an afferent-efferent pathway and cerebral input. This voluntary muscle response may be too slow to manage the ground reaction forces induced from the high risk maneuvers encountered during competitive play. Functional proprioceptive training can increase the speed and efficiency of motor responses through the creation of motor engrams that bring functional activities from cerebral to brain stem level control. The goal of the functional proprioceptive training is to bring the athlete to a level of athletic skill and ability equal to the preinjury state, especially in females and all patients with anterior cruciate ligament reconstructed knees.

**Development of Functional Dynamic Balance**

The first level of proficiency that must be attained before return to sports participation is the ability of the injured knee to maintain balance and stability. Adequate groundwork for dynamic stability proficiency should be established through postoperative rehabilitation.
Stabilometry is a tool that can be used to assess the athlete’s single-leg balance aptitude. Females have a greater loss of single-leg postural balance when returning from a knee injury when compared with males. They also will return to their preinjury state slower than their male counterparts. Therefore, progression through the early stages of sports reentry may be delayed for female athletes. A standard level of proficiency in postural balance before return to sport is important to protect athletes from reinjuring the affected joint. Tropp et al reported that athletes who could not accomplish postural balance within two standard deviations of normal had a significantly higher risk of injury. Increased proficiency in bipedal and single-leg balance can be gained through balance board training. Training progressions should begin with patients early in physical therapy with balance board activities with the athlete in a bipedal stance and progress to single-leg drills in more advanced phases. Early goals are to have the patient maintain stance on the board regardless of ability to control board position. As balance improves the athlete should move to a more flexed athletic position and should maintain stance on the board with greater control of movement. The trainer should encourage the athlete to bring visual focus away from his or her feet and incorporate ball drills that provide a distraction from the balance task (Fig 8). The balance board training provides an effective method for programming the neuromuscular system to send afferent unbalanced stance information, provide the efferent response, and then process the difference between actual movement and the intended movement. This process of neural recognition and muscular response helps develop motor engrams that work to correct future motor control errors. The balance board training will provide hundreds of such engramming opportunities per exercise bout. Improvement of an athlete’s postural balance should decrease risk of reinjury. Tropp et al were able to reduce injury rates in athletes returning to sport from prior injury with 10 weeks of balance board training. Another progressive balance board protocol significantly reduced knee injuries in elite soccer players. Several authors advocate the use of balance board proprioceptive training well past the acute postsurgical rehabilitation phase, not only for restoration of functionality, but for its prophylactic effect on ligament reinjury.

Development of Functional Neuromuscular and Proprioceptive Symmetry

A secondary proficiency level that must be assessed early in functional proprioceptive train-
ing is the athlete’s ability to achieve symmetric bipedal gait. Proficient walking gait should have been established previously, although running gait may not have been corrected to the preinjury form. A running gait retraining program improves symmetry of lower extremity musculature contribution, which may prevent abnormal loading of the ligaments and soft tissue and increase strength and endurance during sports competition. Gait retraining is done best on a treadmill in front of a mirror to provide simultaneous visual and verbal trainer feedback to the athlete. An early goal in gait retraining is to normalize ROM in the involved and the noninvolved limbs. The involved limb often has limited joint ROM, especially at the hip. Incline treadmill running can increase ROM across all joints, but especially at the hip. Care should be taken to monitor the athlete for signs of patellofemoral pain and address this issue as it arises. Backwards incline training (Fig 9) also should be used to increase ROM and to increase quadriceps functional strength while simultaneously reducing patellofemoral stress. The ability of inclined backwards training to increase functional quadriceps strength and limit patellofemoral stress was shown by Snyder-Mackler and coauthors, who reported increased functional gait with improved quadriceps strength after the use of inclined backwards treadmill training. In addition to the ROM and strength benefits from this training, the athlete may create neuromuscular engrams that will prove useful when their sport requires backward locomotion. Once the athlete has increased lower extremity joint ROM to normal levels and has attained lower extremity symmetry, treadmill speeds can be increased to assess the athlete’s sprinting form. Sprinting will continue to improve ROM, especially at the hip and the ankle. Attention should be directed toward obtaining a normal rhythmic stride. An unbalanced sprinting rhythm is indicative of an unbalanced limb contribution and is most evident through the audible monitoring of foot contact. If the athlete presents with this problem of unbalanced sprinting gait, the contributing factors are likely either pain or limited ROM in the involved leg. If patellofemoral pain and decreased joint ROM are determined to be the limiting factors, then increased backwards running may assist the athlete through this progression. Pain-free symmetric sprinting gait should be the ultimate goal of this proficiency level.

Simultaneous gait retraining and a progressive plyometric program teaches the athlete to properly initiate, control, and decelerate ground reaction forces that he or she will encounter in competitive play when jumping, landing, and cutting. Special attention should be directed toward the female athlete, because she often is ligament dominant. Ligament dominance results in high knee valgus moments and high ground reaction forces. During single-leg landing, pivoting, or deceleration, the motion of female athlete’s knee typically is directed by
the ground reaction force, rather than by the athlete’s musculature. To correct ligament dominance in female athletes, a neuromuscular training program must be designed to teach the athlete to control dynamic knee motion in the coronal (valgus and varus) plane. One concept that the athlete is taught is that the knee is a single-plane hinge, not a ball and socket joint. Reeducation of the female neuromuscular system away from multiplanar motion of the knee to dynamic control of knee motion in the sagittal plane alone can be achieved through a progression of plyometric exercises. Initially, the physical therapist or other rehabilitation specialist should choose movements that allow the athlete to gain proper joint kinesthesia during jumping and landing. Correction of ligament dominance must be accomplished through heavy focus on proper form and technique. Jumping and landing technique should be evaluated critically by the trainer or therapist and constant feedback should be given to the athlete in a manner similar to that given when teaching a specific skill required for sport. Verbal feedback such as soft-silent landing, straight as an arrow, land light as a feather, and touch and go is repeated to promote proper technique. Re-programming the neuromuscular system in females requires significant interaction between therapist or trainer and athlete, because the therapist or trainer must be diligent to provide sufficient feedback to develop permanent neuromuscular programs.

What We Have Learned
At least five important conclusions can be made from this review of the literature with respect to the loss and return of proprioception after ligament rupture and reconstruction and the assessment of proprioception before and after ligament injury and during the rehabilitation process. First, after anterior cruciate ligament reconstruction, patients continue to have deficits in proprioception and neuromuscular joint control at least 6 months and for as much as 1 year postoperatively and in some cases beyond 1 year when compared with a control group. Second, patients with anterior cruciate ligament deficiency have impaired proprioception and neuromuscular control of the knee in the involved and noninvolved limbs when compared with a control group. Third, when assessing proprioception and neuromuscular control of patients with either anterior cruciate ligament deficiency or after reconstruction, the contralateral limb may not be a suitable control because of the bilateral deficits. Fourth, it is important to incorporate beginning, intermediate, and advanced proprioceptive training exercises throughout the postoperative rehabilitation protocol. Finally, females with anterior cruciate ligament deficient knees and after anterior cruciate ligament reconstruction possess greater deficits in proprioception and neuromuscular control of the knee and possibly more functional instability than their male counterparts.

Future Research Challenges
Determination of the functional instability of a patient with an anterior cruciate ligament deficient knee is a problem that has challenged researchers and clinicians for decades. Previous studies have established that anterior cruciate ligament deficiency results in mechanical instability; however, functional instability in these patients is significantly more difficult to determine. Therefore, the challenge presented to researchers and clinicians is to determine means of assessment, diagnosis, prescreening for functional instability in patients and athletes and to enhance rehabilitation and prophylactic intervention protocols. A final challenge is to determine precisely how long after surgical reconstruction functional deficits exist in these populations.

References


