Published in final edited form as:

Sports Med. 2018 June ; 48(6): 1303–1309. doi:10.1007/s40279-018-0889-1.

Analysis of Lower Extremity Proprioception for Anterior Cruciate Ligament Injury Prevention: Current Opinion

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Abstract

Lower extremity musculoskeletal injuries – such as ACL injury – are common, and the majority of those injuries occur without external player contact. In order to prevent non-contact musculoskeletal injuries, athletes must rely on accurate sensory information (such as visual, vestibular, and somatosensory) and stabilize joints during athletic tasks. Previously, proprioception tests (the senses of joint position, movement, tension or force) have been examined using static tests. Due to the role of proprioception in achievement of joint stability, it is essential to explore the development of dynamic proprioception tests. In this current opinion, the basic background on proprioception is covered, and the research gaps and future directions are discussed.

Keywords

proprioception; ACL; knee; thigh; ankle

1. Background

The lower extremity musculoskeletal structures experience ground reaction forces (GRF) that are multiple times body weight during athletic maneuvers (such as pivoting, acceleration, deceleration, and landing) [1]. One of the most common and devastating injuries in the lower extremity is anterior cruciate ligament (ACL) injury, and the majority of ACL injuries occur without significant external contact other than GRF (commonly referred as a non-contact ACL injury) [2]. Epidemiological studies have demonstrated that female

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Conflicts of Interest

Takashi Nagai, Nathan Schilaty, Jeffrey Strauss, Eric Crowley, and Timothy Hewett declare that they have no conflicts of interest relevant to the content of this article.

athletes experience ACL injuries at a higher rate than male athletes [3, 4]. Landing with less knee flexion angle and greater valgus angle moments are common mechanisms of non-contact ACL injury [5, 6]. As the majority of ACL injuries are non-contact in nature [7, 8], these injuries likely occur due to aberrant biomechanical loading and thus are potentially preventable. In order to avoid potential injuries, the nervous system must acquire real-time sensory information regarding the forces and moments affecting each joint and adequately supply either feedforward or reflexive motor commands to the musculature to counteract these forces and moments, and thus stabilize the joint [9, 10]. A failure to provide adequate neuromuscular responses from the provided sensory information can result in lower extremity musculoskeletal injuries such as rupture of the ACL [2]. It has been demonstrated that female athletes who later suffered an ACL injury exhibited deficits in detecting trunk position and lower reaction time in responses to perturbation [11, 12]. Since few prospective studies have incorporated proprioception tests of the lower extremity, this current opinion discusses the background and rationale for developing dynamic proprioception tests as a screening tool for non-contact ACL injury.

The sense of proprioception – the ability to know where the body is in space, whether conscious or unconscious – is provided by the sensory afferents about the joint. These multiple sensory afferent inputs and their associated neurological systems enhance awareness of posture, movement (kinesthesia), joint position, limb velocity, changes in equilibrium and weight, and resistance of objects in relation to the body [13]. In the research setting, proprioception is commonly assessed with 1) threshold to detect passive motion (TTDPM): the ability to detect the initiation of passive joint movement, or 2) joint position sense (JPS): the ability to reproduce the target joint position actively or passively [14]. Due to the complexity of proprioception and its role in joint stability, the current manuscript focuses on description of the physiological basis of TTDPM and JPS in the lower extremity proprioception literature, identification of the research and clinical gaps, and discussion of the needs for new approaches.

2. Physiological Basis of TTDPM and JPS

The muscle spindles contain primarily type Ia and type II sensory fibers, as well as gamma and beta motor neurons, and are sensitive to the changes in length of the muscle fascicles during slow and fast joint movement or at the initiation of the joint movement [15–17]. Therefore, based on the anatomical and physiological functions, the muscle spindles are thought to be primarily responsible for TTDPM [18]. Secondly, the skin and articular structures such as ligaments, menisci, and capsules also contain both slow- and fast-adapting sensory fibers [19], and those mechanoreceptors are thought to contribute to TTDPM [18].

JPS is another commonly used submodality of proprioception tests in the clinical testing. Muscle spindles and the mechanoreceptors of skin and articular structures are likely involved in JPS [18]. Although muscle spindles can be involved in both TTDPM and JPS, those two proprioceptive senses (of joint position and movement) are independent of each other as demonstrated by no significant correlations between those tests within the same individuals [14]. JPS is thought to be influenced by efferent outflow signals by motor commands in addition to the cutaneous, articular, musculotendinous mechanoreceptors [20].

During examination of knee proprioception, TTDPM is influenced by the direction of the movement and initial starting position [21]. Individuals can detect the passive motion of the joint faster during TTDPM testing when their joints are positioned at the end-range and moving toward the terminal end-range direction [21]. In addition, female athletes exhibit poor TTDPM (longer time to detect the movement) toward the knee terminal extension and internal rotation [22, 23]. This is significant as the ACL becomes taut at with extension and internal rotation and demonstrates the common mechanism of a non-contact ACL injury [5, 6]. Diminished sensitivity of knee movement toward these particular directions could pose potential risk of the ACL injury, particularly in female athletes, because the ACL is loaded at this position [22, 23]. Individuals with the ACL injury exhibit difficulty with detection of knee movements toward the terminal extension [21]. Furthermore, reconstruction surgery may not fully restore the proprioceptive sense [24, 25]. One potential explanation of mixed results from previous studies is that mechanoreceptors that are normally found in the intact ACL may not be fully restored after reconstruction surgery in human [26]. Muscle spindles and other mechanoreceptors must compensate for the loss or diminished articular mechanoreceptors of ACL, and individuals must gradually adapt after the ACL rupture and reconstruction through rehabilitation exercises [27].

JPS after active movements is more precise than after similar passive movement [28]. As an example, individuals with cerebellar disease performed a task at a similar level to controls under passive proprioception. Once the movements were active, controls performed the tasks better, which indicated that the cerebellum played a crucial role in normal JPS [28]. The cerebellum contributes to movement control by prediction of body state (i.e., position, velocity) from a copy of motor commands (i.e., efferent copy) and stored knowledge of dynamic properties of the body [28]. Consequently, cerebellar prediction would be essential for movement because it would reduce dependence on time-delayed feedback from peripheral sensors, and contribute to the memory of position [29]. Clinically, the cerebellum is tested with finger-to-nose and finger-to-finger tests with eyes open and then closed to verify the ability of the individual to coordinate sensorimotor systems with simultaneous memory of previous joint position. These tests are available for the lower extremity, but are much more limited in terms of recreated joint position.

Both TTDPM and JPS must be consciously perceived and interpreted. In other words, these tests likely rely on the sensation conveyed to the cerebellum via the posterior column. Reliance of JPS on the cerebellum may indicate that this test might be better suited to evaluate unconscious proprioceptive sensation via the dorsal spinocerebellar tract or the whole sensorimotor loop. JPS is relatively easy to test clinically and can be performed in both open-kinetic chain and closed-kinetic chain (dynamic assessment of JPS in standing/squatting) [30–32]; however, it has been criticized for high measurement variability, lack of reliability, and questionable validity of the tests [33, 34]. Therefore, JPS tests would require more refinement to be clinically relevant. Recent work indicates that the sense of limb position should also be thought of in dynamic situations and the cerebellar processing may be part of a predictive mechanism for proprioceptive sense of spatial and temporal information [35, 36].

3. Sensorimotor Integration and Leg Stiffness Regulation

As presented previously, muscles spindles likely play a major role in the sensorimotor system [37]. To demonstrate its dominance in the sensorimotor system, more axons are devoted to transmission of signals to and from muscle spindles than to activation of the muscles themselves [37]. This evidence implies an important role for sensorimotor integration from muscle spindles as well as the need to adjust these signals in real-time at their source via fusimotor action. The muscle spindle system can regulate the resting tone and stiffness of the muscles as well as the excitability of the alpha motor neuron [9, 38, 39]. Increased resting stiffness of the muscles can provide the first line of defense less than 50 milliseconds against potential perturbation of the joint [40, 41]. Since ACL injury likely occurs less than 100 milliseconds after initial foot contact with the ground during landing, deceleration, and lateral pivoting maneuvers, the pre-activation of the lower extremity muscles is important for preparation of the muscle to resist a high impact force and quickly react for the subsequent push-off after contact [33].

The muscle spindles contain gamma motor neurons that adjust stretch sensitivity and can influence the alpha motor neuron and consequently neuromuscular control; hence, individuals with improved TTDPM exhibit safer landing technique with greater knee flexion angles at initial contact [42]. This finding demonstrates that individuals with improved proprioception exhibit superior neuromuscular control to achieve functional joint stability during athletic maneuvers. In particular, dancers who regularly train jumps and landings to achieve the desired aesthetics of a smooth landing have very few ACL injuries [43]. Biomechanical analyses revealed that dancers land with higher lower body stiffness and greater activation of the hamstrings than basketball players [44]. Gymnasts and dancers also are known to have better TTDPM when compared to healthy controls [45, 46]. Based on those aforementioned studies on gymnasts and dancers, it is speculated that specific types of exercises and training in their practices might have positively influenced their proprioception and resultant neuromuscular control.

4. Effects of Exercises on Proprioception

A systematic review of the components of neuromuscular training in ACL prevention programs has identified that a combination of plyometric, balance, stretching, and strength exercise did better to improve neuromuscular control than one component exercise [47]. Most programs incorporated those exercises as part of a warm-up routine. Plyometrics with feedback can improve landing technique that likely result in less ACL injury risk [48, 49]. Additionally, one's lower extremity proprioception can likely be enhanced by plyometric exercises. A basic form of plyometric exercise such as jump rope training has shown to improve knee JPS in mid-teen female volleyball players [50]. Skipping/jogging with other types of exercises – such as stretching, ball drills, and dynamic movements – as part of a 25-minute warm-up has also shown to improve knee JPS in semi-professional soccer players [51]. Eccentric loading during plyometric exercise may provide sufficient stimuli for the musculotendinous mechanoreceptors to adapt and fine-tune to improve proprioception. In previous studies, unaccustomed eccentric training resulted in a diminished JPS [30]. This eccentric exercise likely disrupted the integrity of the muscle spindles and resulted in an

increased error of JPS immediately after the exercise [52]. This disruption in proprioceptive sensation after eccentric exercise represents a mismatch in the sensorimotor loop and requires adjustments in the stiffness regulation. However, what's more important to know is that as a long-term outcome, the human body adapts to eccentric exercise and develops a more keen proprioceptive sense [53].

Other components of an ACL prevention neuromuscular training program are likely involved in improving proprioception. For example, both static and dynamic stretching exercise as a part of warm-up has resulted in improved JPS [54, 55]. However, stretching alone (not as a part of warm-up) might not provide sufficient stimuli to have any meaningful changes on proprioception [56]. Another type of warm-up program with balance exercise had an effect to significantly improve JPS [57]. Although the exact mechanism of this adaptation is not fully known, perturbed balance can increase reflex sensitivity – likely mediated by the gamma-muscle spindle system – and increase the rate of force development and promote co-contraction of muscles to stability the joint [58, 59]. Despite the evidence of the effects of exercise on proprioception, an efficacious means to train the sensorimotor system should be explored further.

5. Identification of the Gaps in Literature

The importance of proprioception as a clinical outcome measure is well recognized, but the best measurement technique has yet to be determined [33]. Muscle stiffness in relation to proprioception is not commonly measured in sports medicine literature. Stiffness is a measure of resistance of elastic materials to deformation and is an intrinsic property of muscle. Muscle stiffness is derived both *passively* from connective tissue collagen/elastic fibers and *actively* with alpha- and gamma-motor neuron co-activation (generating the actin-myosin cross-bridges to increase muscle stiffness when needed) [9, 38, 60]. Muscle stiffness directly contributes to joint stabilization. Aberrant muscle stiffness can leave a joint unable to resist potentially deleterious biomechanical forces and result in injury [39, 61]. Overall, joint stabilization is a synergistic compendium of bone, joint capsule, ligaments, muscles, sensory receptors, and their spinal and cortical neural connections [39]. Of these contributors to joint stabilization, the neuromuscular components are potentially modifiable [38, 61–63]. Enhanced proprioception via sensorimotor integration could enhance neuromotor drive and allow for improved activation and reflexive outcomes for reduction of injury with *active* feedforward and feedback controls [9, 38, 39, 60]. More recently, mechanical property of muscles and tendons in human can be measured with the diagnostic musculoskeletal ultrasound elastography [64]. This technology may allow us to explore the relationship between the proprioception, stiffness, and muscular strength simultaneously.

The previous objective measures of TTDPM and JPS, either passive or active, have failed to produce objective sensitivity for improvement of prevention and rehabilitative paradigms in sports medicine. In addition, the tests themselves are not physiologically relevant to athletic tasks typically encountered (i.e. pivoting, cutting, landing). As proprioception encapsulates a large variety of highly adapted and specific receptors types (i.e. Meissner corpuscles, Pacinian corpuscles, Merkel discs, Golgi tendon organs, muscle spindles, and free nerve endings) found in the skin, fascia, muscle, and joints, the variability from one athlete to

another is minimal and often times the objective measures have too much error to draw adequate conclusions. Thus, it is imperative to implement proprioceptive tests that allow for more physiological movement and speeds similar to what athletes would encounter. In other words, more ‘dynamic’ proprioceptive tests are warranted in future research than the ‘static’ approach of the past. Some ‘dynamic’ proprioceptive tasks have been performed, such as squats with a target thigh/knee angle, but once again the variability is sufficiently high that the data has provided limited insight into the proprioception ability of the athletes which is already variable [30–32]. Rather, future tests and their corresponding tasks must be able to effectively analyze factors associated with proprioception on the unconscious level. Suggestions for this type of testing include reaction tests (i.e. split-belt treadmill or unexpected surface) or a high-speed variant of TTDPM that would safely perturb the lower limbs from a resting position (Fig. 1). These tests would employ an unconscious proprioceptive sensorimotor loop coupled with measures of neuromuscular activity via electromyography at specific joint positions where ACL injuries commonly occur. With these measures, data extraction could evaluate muscle stiffness (both passive and active), neuromuscular delay, peak torque production, rate of force development, and neuromotor activation.

Ultimately, after rehabilitation from musculoskeletal injuries, surgeries, or concussions, athletes must prepare to return-to-sport. Recent epidemiological studies demonstrate that those athletes who were cleared to play had higher incidence of lower extremity musculoskeletal injuries [7, 65]. Therefore, return-to-sport criteria should be comprehensive. Strength measurements alone as a criteria for return-to-sport after serious lower extremity injuries or surgeries will likely be inadequate as the individuals may have full strength but still have functional instability [33]. Clinically, muscular strength can be assessed using an isokinetic dynamometer. However, the integrity of the sensorimotor system or gamma-alpha motor neuron coupling should also be examined. TTDPM provides both reliable and valid values about the joint movement at the slower speed. Consequently, high-speed TTDPM might be of interest to explore in future studies (Fig. 1). In addition, relationships among peak muscular strength, high-speed TTDPM, and musculotendinous stiffness could provide an insight of one’s readiness from the sensorimotor perspective (Fig. 2). Muscular pre-activation and the regulation of leg stiffness can be examined using the electromyography and musculoskeletal ultrasound, yet another potential avenue for future investigations.

6. Conclusions

Based on epidemiological studies, the current return-to-sport criteria may not be sufficient to assess athletes’ preparedness due to a lack of tests to examine the sensorimotor system. Traditional proprioception tests including JPS and TTDPM can provide valuable information about athletes’ ability to sense their joint position and movement; however, those tests are not physiologically relevant to athletic tasks typically encountered in sports. A test to examine ones’ ability to perceive movement and to react to a valid stimulus can potentially incorporate several important variables to achieve joint stability (ability to rapidly detect joint movement and respond), muscle stiffness, neuromuscular delay, peak torque production, rate of force development, and patterns of neuromotor activation. A simple yet

in-depth dynamic assessment could be added to the current battery of return-to-sport evaluations once the reliability, precision, and validity are established.

Acknowledgments

Funding

The authors acknowledge funding from the National Institute of Arthritis and Musculoskeletal and Skin Diseases: R01AR056259 and R01AR055563 to TEH and L30AR070273 to NDS, and from the National Institute of Child Health and Human Development: K12HD065987 to NDS.

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Key Points

1. Joint position sense and movement are commonly assessed statically, as joint position sense (JPS) and threshold to detect passive motion (TTDPM), respectively.
2. The muscle spindles are sensitive to changes in length of the muscle fascicles during slow and fast joint movement and contribute to both senses (i.e. JPS and TTDPM). The muscle spindles also contain gamma motor neurons and regulate muscle tone and stiffness in order to protect the joint from perturbation and extreme loads.
3. In order to fully assess one's integrity of both sensory and motor function as a surrogate measurement of preparedness against perturbation, an example of dynamic proprioception is described. It involves high-velocity TTDPM and reactive torque development in the same protocol.

Figure 1. High-velocity threshold to detect passive motion (hvTTDPM)

Two control subjects respond to the hvTTDPM from an accelerating dynamometer. Note the differences in the subjects abilities for rate of torque development even though response times are similar.

Figure 2. Stiffness from high-velocity threshold to detect passive motion (hvTTDPM)

The data from this plot is from the same data that is represented in Figure 1. The initial dashed line represent the passive stiffness slope (similar between subjects) and the second dashed lines represent the active stiffness generated in response to the stimulus. The two subjects differ in their ability to generate active muscle stiffness.