Proprioception: The Sensations of Joint Motion and Position

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Sherrington in 1906 stated that the reaction of an animal to stimulation of one of its exteroceptors excites certain tissues, and the activity thus produced in these latter tissues excites in them their receptors, which are the proprioceptors. Awareness of the body and its relationship with the surrounding environment is mediated by sensation. The history of sensation dates back to the Greek philosopher Aristotle, who was the first to describe the five senses. Sir Charles Bell later included sensation as it relates to limb position and motion as the "sixth sense".

Sensation is the fundamental ingredient that mediates the proprioceptive mechanism. The articular structures of the body act as sensory chambers which relay proprioceptive information between specific neural pathways within the
peripheral nervous system (PNS) and central nervous system (CNS). These neural pathways also transport the necessary sensorimotor information which modulates muscle function. The articular structures as defined in this manuscript include the ligamentous tissue within and surrounding movable joints, and the adjoining musculotendinous tissue that cross and insert around these joints. Articular sensation will be defined as the sensations emanating from these articular structures.

The terminology related to articular sensation is often misunderstood and used inappropriately, which has lead to confusion and a lack of appreciation for these mechanisms. Articular sensations are described as *proprioception* and *kinesthesia*. There is considerable discrepancy in the definitions of these two terms as related to their physiological functions. Proprioception and kinesthesia have been defined as a complex of sensations with reference to joint motion and position. Visual and vestibular inputs subserve proprioception, and are also included within the sensory complex. For the purpose of this manuscript, proprioception will be defined as a specialized variation of the sense of touch that encompasses the sensations of joint motion (kinesthesia) and joint position (joint position sense).

The neural innervation of articular structures is supplied by peripheral receptors located within the tissue that surrounds these structures (i.e., the joint, muscle and cutaneous (skin) layer). These receptors include nociceptive free nerve endings that signal pain and touch, and mechanoreceptors which signal mechanical deformation of soft tissue, also referred to as "deep touch".

Scientists have identified mechanoreceptors in both animal and human tissue, and there appears to be a wide distribution throughout the body. Mechanoreceptors have been identified in the shoulder, knee, and ankle joints, as well as in their musculotendinous attachments and the overlying cutaneous
layer. There are four types of mechanoreceptors with each type displaying different shapes, threshold levels, locations and adaptive properties. Type I receptors are the Ruffini endings located in the superficial layers of joint capsules, and the muscle spindle/Golgi tendon organ (GTO) complex, located within the musculotendinous unit. These receptors have a low threshold for activation, and are slow-adapting. The second Type of receptor is the Pacinian corpuscle located in the deep layers of joint capsule. This receptor is quick adapting, and has a very low threshold for activation. The third type of mechanoreceptor is the Ruffini corpuscle located in the individual joint ligaments. This receptor is slow-adapting and has a higher threshold for activation than the type I receptors. Type IV receptors are the nociceptive free nerve endings situated in the muscle, ligament and cutaneous tissue layers and are sensitive to touch, pressure, and pain. Cutaneous mechanoreceptors have been found to resemble the Ruffini and Golgi type receptors in their physical characteristics and are therefore classified in either the type I, II, or II groups.

Mechanoreceptors function by transducing some form of mechanical deformation into a frequency-modulated neural signal which is transmitted via afferent and efferent pathways. The muscle spindle and GTO using the same pathways function by transducing information concerning muscle length and tension under static and dynamic conditions. The major difference between the function of the muscle spindle and the GTO is that the muscle spindle monitors muscle length, while the GTO monitors muscle tension. An increased stimulus of deformation, tension, or length within articular structures is coded by an increased afferent discharge rate or a rise in the population of activated receptors. Mechanoreceptors demonstrate different adaptive properties based on their response to a continuous stimulus. Quick-adapting mechanoreceptors, such as the Pacinian corpuscle, decrease their discharge rate to extinction within
milliseconds of the onset of a continuous stimulus. Slow-adapting mechanoreceptors, such as the Ruffini ending, Ruffini corpuscles, and the muscle spindle/GTO complex, continue their discharge in response to a continuous stimulus. Quick-adapting mechanoreceptors are very sensitive to changes in stimulation and are, therefore, thought to mediate the sensation of joint motion. Different populations of slow-adapting mechanoreceptors are maximally stimulated at specific joint angles, and thus are thought to mediate the sensation of joint position and change in joint position. These mechanoreceptors are especially sensitive at the extreme ranges of joint motion.

There is considerable debate among scientists over the relative contribution to proprioception of muscle receptors versus joint receptors, with traditional views emphasizing joint mechanoreceptors and more contemporary views emphasizing muscle receptors. Evidence suggests that joint receptors and muscle receptors are probably complementary components of an intricate afferent system in which each receptor modifies the function of the other. With the identification of these receptor types, and the knowledge of their function, it appears that the soft tissue structures of muscles and joints contain the neural components necessary for the awareness of joint motion (rapidly adapting receptors, e.g. Pacinian corpuscles), joint position (slowly adapting receptors, e.g. Ruffini endings and corpuscles, and the muscle spindle/GTO complex), pain and touch (free-nerve endings).

This combination of both muscle and joint receptors forms an integral component of a complex sensorimotor system that plays a role in the proprioceptive mechanism. The proprioceptive mechanism is part of a feedback-feedforward system initiated by the activation of mechanoreceptors. The sensory (afferent) input from the mechanoreceptors is relayed by the PNS to the CNS. The CNS responds to the afferent stimulus by discharging a motor (efferent)
signal which modulates effector muscle function by controlling joint motion and/or position.

The afferent and efferent pathways involved with this complex system mediate proprioception at three distinct levels within the CNS. At the **spinal level**, proprioception operates unconsciously with reflexes subserving movement patterns that are received from higher levels of the nervous system. This provides for reflex splinting during conditions of abnormal stress about the joint and has significant implications for rehabilitation. The muscle spindles play a major role in the control of muscular movement by adjusting activity in the lower motor neurons.

The second level of motor control is at the **brain stem** (basal ganglia, and cerebellum), where joint afference is relayed to maintain posture and balance of the body. The input to the brain stem about this information emanates from the joint and muscle proprioceptors, the vestibular centers in the ears, and from the eyes.

The final aspect of motor control includes the highest level of CNS function, the **motor cortex**, and is mediated by cognitive awareness of body position and motion. Proprioception at this level functions consciously, and is essential for proper muscle and joint function in sports, activities of daily living, and occupational tasks. These higher centers initiate and program motor commands for voluntary movements. Movement patterns that are repetitive in nature can be stored in the subconscious as central commands, and can be performed without continuous reference to consciousness.

The disruption of muscle and joint mechanoreceptors from physical trauma results in partial deafferentation of the joint and surrounding musculature, thus resulting in diminished proprioception. Partial deafferentation and sensory deficits can predispose to further injury, and contribute to the etiology of
degenerative joint disease (arthritis) through pathologic wearing of a joint with poor sensation. It is unclear whether the proprioceptive deficits that accompany degenerative joint disease are a result of or contribute to the etiology of the pathologic process. Partial deafferentation has also been shown to alter the musculature’s ability to provide co-contraction (dynamic) joint stabilization by antagonistic and synergistic muscles, also resulting in the potential for reinjury. Additionally, mechanoreceptor function is speculated by scientists to have a genetic component which can influence proprioceptive acuity in certain individuals. Contemporary research has investigated these hypothetical models, and some interesting findings have been revealed.

With the demonstration of the neural framework necessary for muscle and joint sensation, investigators have just recently begun to perform functional studies of knee, shoulder, and ankle joint proprioception. Lephart et al. at the University of Pittsburgh have designed a Proprioception Testing Device (PTD) (Figure 1) to functionally assess proprioception (kinesthesia and joint position sense) of the knee and shoulder. The PTD measures the angular displacement of the joint being tested prior to detection of movement by the subject, and measures the patient's accuracy in reproducing selected joint angles. The PTD moves the joint at a constant angular velocity ranging from 0.5°/sec. to 2.5°/sec. A rotational transducer interfaced with a digital microprocessor counter provides angular displacement values.

Functionally, kinesthesia is assessed by measuring threshold to detection of passive motion (TTDPM), while joint position sense is assessed by measuring reproduction of passive positioning (RPP) and reproduction of active positioning (RAP). TTDPM, when tested at slow angular velocity (0.5 -2.5 °/sec), is thought to selectively stimulate the Ruffini mechanoreceptors, and because the test is performed passively, it is believed to maximally stimulate joint receptors while
minimally stimulating muscle receptors. In shutting down muscle activity, TTDPM is often chosen to assess afferent activity following ligament pathology. RAP, although usually performed at slow speed, stimulates both joint and muscle receptors and provides a more functional assessment of the afferent pathways. Neither TTDPM, RPP, nor RAP provides an assessment of the unconscious reflex arc believed to provide dynamic joint stability. The assessment of reflex capabilities is usually performed using EMG interpretation of firing patterns of those muscles crossing the respective joint.

Concerning the knee joint, Barrick and Skinner identified a pattern of enhanced kinesthesia in trained dancers, while Lephart et al. has more recently revealed enhanced kinesthesia in intercollegiate gymnasts. Barrick and coworkers demonstrated that a proprioceptive deficit exists after ACL disruption, and Lephart et al. have found that a deficit continues after reconstructive surgery. Barrett and coworkers demonstrated a decline in joint position sense (JPS) with osteoarthritis, and Skinner et al. further demonstrated decreased kinesthesia with increasing age.

The perception of joint position and motion in the shoulder is essential for placement of the hand in upper limb function. In addition, proprioception may play an important role in dynamic shoulder stability and modulation of muscle function. Recent work by Smith and Brunolli has demonstrated that a sensory deficit occurs in patients with recurrent, atraumatic, anterior instability. In a similar group of subjects with unilateral, traumatic, recurrent, anterior shoulder instability, Lephart et al. demonstrated both TTDPM and RPP deficits, similar to the findings of Smith and Brunolli. These two studies elucidate a pattern of proprioceptive deficits in unstable shoulders. Additionally, in a population of college age individuals without any history of shoulder injury, Lephart et al. found minimal variation in kinesthesia and no differences between dominant and
nondominant shoulders. Additionally, the uninvolved shoulders of subjects in Lephart et al.’s instability study demonstrated proprioceptive measurements similar to those of the normative population without shoulder dysfunction. Although we have not yet had the opportunity to study reflex stabilization, one can hypothesize that altered proprioception in unstable shoulders may influence the dynamic mechanisms of joint restraint. This would therefore, indicate the necessity of integrating shoulder kinesthetic and joint position sense exercises as a part of shoulder rehabilitation. It is logical to assume that methods to improve proprioception in patients with shoulder disorders could improve shoulder function and decrease the risk of reinjury.

The ankle joint has also been shown to display proprioceptive deficits similar to those deficits displayed in the knee and shoulder joints. These deficits also result from joint injury and/or chronic instability. "Proprioceptive training" techniques following acute and chronic ankle sprain injuries are the most widely used compared with other injuries, yet these techniques have only empirical evidence of effectiveness and remain untested.

For years, knee surgeons have postulated that the sensory loss associated with ligamentous injury may affect the results of surgical repair and reconstruction. Some orthopedic surgeons advocate certain reconstructive techniques due, in part, to increased afferent preservation. Theoretically, operative techniques can restore proprioception directly through reinnervation of damaged structures or indirectly through restoration of appropriate tension in capsuloligamentous structures. For example, acute ACL repair may facilitate mechanoreceptor regeneration along with maintaining anatomic relationships. The extent of reinnervation in the reconstructed ligament and its relationship to revascularization is unknown at the present and needs to be further addressed.
Bracing and wrapping have also been thought to serve a sensory function in addition to a mechanical function. Barrett and coworkers found that an elastic bandage enhanced joint position sense in patients with osteoarthritic knees as well as in patients after total knee arthroplasty. Lephart et al. found enhancement of kinesthesia in ACL reconstructed subjects with the use of a commercially available neoprene sleeve (Pro Orthopedic Devices, Inc.). Since proprioception is mediated by afferent input from articular, muscular, and cutaneous structures, the neoprene sleeve is thought to augment afferent input by providing increased cutaneous stimulation.

Developing a rehabilitation program that incorporates proprioceptively mediated muscular control of joints necessitates an appreciation for the central nervous system’s (CNS) influence on motor activities at the three distinct levels of motor control. With these three levels of motor control in mind, mediated in part by joint and muscle afferents, one can begin to develop rehabilitation activities to address proprioceptive deficiencies. The objectives must be to stimulate the joint and muscle receptors in order to encourage maximum afferent discharge to the respective CNS level. At the spinal level, activities that encourage reflex joint stabilization should be addressed. Such activities include sudden alterations in joint positioning that necessitate reflex muscular stabilization. Balance and postural activities, both with and without visual input, will enhance motor function at the level of the brain stem. While consciously performed joint positioning activities, especially at joint end ranges, will maximally stimulate the conversion of conscious to unconscious motor programming.

If a proprioceptive deficit goes undetected, complete rehabilitation may be inhibited, and may also predispose the athlete to reinjury. Thus it is clear, based on the results of these studies mentioned, that any comprehensive rehabilitation
program designed to return athletes to preinjury levels of activity following muscle or ligament injuries should include an extensive proprioception element.

Summary

Proprioception is a specialized variation of the sense of touch that encompasses the sensations of joint motion (kinesthesia) and joint position (joint position sense). Mechanoreceptors are the sensory receptors located in soft tissue articular structures. Three distinct morphological types of mechanoreceptors are situated within ligamentous tissue (Ruffini endings, Pacinian corpuscles, and Ruffini corpuscles), and two types of mechanoreceptors appear in the musculotendinous tissue that surrounds the joint (muscle spindles and GTOs). Mechanoreceptors function by transducing some form mechanical deformation into a frequency modulated neural signal which is transmitted via afferent and efferent pathways. The disruption of muscle and joint mechanoreceptors from physical trauma results in partial deafferentation of the joint and surrounding musculature, thus resulting in diminished proprioception. The results of current investigations indicate the need for proprioceptive training during any rehabilitation program designed to return athletes to preinjury levels of activity following ligament and muscle injuries.
References

LEGEND OF FIGURES

FIGURE 1: Proprioceptive Testing Device: a= rotational transducer; b= motor; c= moving arm; d= stationary arm; e= control panel; f= digital microprocessor; g= hand-held disengage switch; h= pneumatic compression boot; i= pneumatic compression device. TTDPM is assessed by measuring the angular displacement until the subject senses motion in the knee.