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Review

Assessing proprioception: A critical review of methods

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Abstract

To control movement, the brain has to integrate proprioceptive information from a variety of mechanoreceptors. The role of proprioception in daily activities, exercise, and sports has been extensively investigated, using different techniques, yet the proprioceptive mechanisms underlying human movement control are still unclear. In the current work we have reviewed understanding of proprioception and the three testing methods: threshold to detection of passive motion, joint position reproduction, and active movement extent discrimination, all of which have been used for assessing proprioception. The origin of the methods, the different testing apparatus, and the procedures and protocols used in each approach are compared and discussed. Recommendations are made for choosing an appropriate technique when assessing proprioceptive mechanisms in different contexts.

Keywords: Joint motion sense; Joint position sense; Kinaesthesia; Movement discrimination; Proprioception

1. Updated understanding of proprioception

Body movement is a fundamental and essential component of human life. In daily activities, most of what a human does in their interaction with the environment is associated with the generation of movement. Further, in competitive sports, precise and coordinated body movement is critical for success. A fundamental shift in the research field of human movement control has occurred in recent decades, largely due to a growing understanding of the role that sensory information plays in neuroplasticity through use-dependent mechanisms.[1] The most important source for the promotion of task-specific neural development is argued to be proprioception.[1–5]

The question "What is proprioception?" has often been asked in the literature.[6] Different conceptualizations of "proprioception" by researchers have led to different definitions, and consideration of their historical emergence is relevant here.

The fundamental anatomical basis for the connection between the brain and limbs was first identified in 1826 by a Scottish physiologist, Charles Bell. Bell wrote that "between the brain and the muscles there is a circle of nerve; one nerve (ventral roots) conveys the influence from the brain to the muscle, another (dorsal roots) gives the sense of the condition of the muscle to the brain".[7] In Bell's view, "muscular sense" refers to a closed-loop system between the brain and the muscles: the afferent pathway from the muscles to the brain and the efferent pathway from the brain to the muscles.

Sixty years later, the English anatomist and pathologist Henry Bastian introduced the term "kinaethesia", derived from two Greek words "kinein" (move) and "aisthesis" (sensation):"I refer to the body of sensation which results from or is directly occasioned by movements . . . kinaesthesis. By means of this complex of sensory impression we are made acquainted with the position and movements of our limbs . . . by means of it the brain also derives much unconscious guidance in the performance of movement generally".[8]

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Subsequently, in 1906, the English neurophysiologist Sir Charles Sherrington coined "proprioception", from a combination of the Latin "proprius" (one's own) and "perception", to give a term for the sensory information derived from (neural) receptors embedded in joints, muscles and tendons that enable a person to know where parts of the body are located at any time. He referred to proprioception as "the perception of joint and body movement as well as position of the body, or body segments, in space".[9]

Currently, both "proprioception" and "kinaesthesis (kinaesthesia)" continue to be used as terms in the published literature. However, specialists from fields such as neurology, neurophysiology, neuropsychology, sports and exercise medicine, and orthopaedic surgery have different interpretations of the two terms. Some researchers define proprioception as joint position sense only, and kinaesthesia as the conscious awareness of joint motion;[10,11] while others consider that kinaesthesia is one of the submodalities of proprioception, and that proprioception as a construct contains both joint position sense and the sensation of joint movement (kinaesthesia).[12–19] Proprioception defined in this way accords with Bastian's conceptualization of kinaesthesis (kinaesthesia), each including both position and movement senses. Although joint position and movement have been considered as two separate sensory entities,[20,21] any movement is accompanied by changes in information regarding both position and movement senses.[22–25] That is, the senses of joint movement and joint position are always associated with each other in daily activities.[26] Consequently, it has been argued that it is appropriate to interpret "proprioception" and "kinaesthesis (kinaesthesia)" as being synonymous.[26–29]

The original definition of proprioception, given by Charles Sherrington when he first used the term, was that proprioception is ". . . the perception of joint and body movement as well as position of the body, or body segments, in space", and the "perceptions of the relative flexions and extensions of our limbs".[9] Here Sherrington refers to proprioception as "perception" of body position and movement. Perception, from the Latin "percepio" (perceive), is the identification, organization, and interpretation of sensory information, in order for humans to internally represent and understand the environment.[30] All perceptions require signals within the nervous system, which derive from physical stimulation of various sense organs.[31] For instance, hearing involves sound waves impacting the eardrum, and vision includes light impinging the retina of the eye and the transduction of these different forms of energy into electrical energy within neurons. Likewise, proprioception requires the stimulation of mechanoreceptors to threshold via body movements (changes of body position). However, a characteristic of perception is that it is not simply the passive receipt of a sensory signal, but rather, perception is shaped by memory and learning.[32]

In this understanding, proprioception can be defined as an individual's *ability* to integrate the sensory signals from mechanoreceptors to thereby determine body segment positions and movements in space.[1,33–37] In other words, proprioception is not merely a physiological property, but rather, it has both physiological (hardware) and psychological (software) aspects.[37,38] To be specific, proprioception is the perception of body position and movements in three-dimensional space, and overall *proprioceptive performance* is determined by the quality of both the available *proprioceptive information* and an individual's *proprioceptive ability*. Thus, the hardware (peripheral mechanoreceptors) provides proprioceptive information to the brain for the software (central processing) to integrate and use.[39]

More specifically, Ashton-Miller et al.[40] have argued that if proprioception is only the afferent (hardware) part of the system, proprioception cannot be trained because there is no capacity to train a signal. In contrast, a recent systematic review by Witchalls et al.[41] has demonstrated that proprioception as a measure of the neuromuscular response to a stimulus must involve sensory input, central processing, and motor output in a closed loop. In light of this latter view, it is insufficient to consider proprioception just as a cumulative neural input to the central nervous system (CNS) from the mechanoreceptors located in muscles, joints and the skin,[42–45] and it is inappropriate to interpret either passive movement detection without muscle activation or a measure of reflex muscle activation[46] as overall proprioceptive ability.

In the past century, (neuro)physiologists have had a strong interest in investigating the roles of peripheral mechanoreceptors in determining proprioception, and have used different techniques, such as vibration or anaesthesia, to differentiate the functional roles of the different mechanoreceptor types.[47–49] However, to execute functional movements in daily activities, exercise, and sports, proprioceptive information from a variety of mechanoreceptors is available for central processing. Therefore a complex array of different sources is utilized, although muscles spindles are seen as the main transducers used to gather proprioceptive information.[21,50] Further, an increasing number of researchers, especially those in exercise and sports, now recognize the importance of central processing in proprioception, when attempting to understand human movement.

For instance, evidence has suggested that central processing in proprioception may play a role in sport performance. Although most body movements in daily activities are automated, conscious attention is required to learn complex skills in sports and exercise, such as when using the foot to control a ball, performing a variety of arm movements in ice skating, or executing Tai Chi movements in a coordinated pattern. Learning movement skills means developing new patterns of movement by processing proprioceptive information appropriately. New neural programs are developed, refined by repetition and transferred to the more fundamental regions of the brain, from where they are executed with less effort and relayed much faster.[51] It has been argued that a novice athlete spends time consciously mastering new movements using a closed-loop system of control, whereas skilled athletes only occasionally use sensory checking for successful execution of relevant movements.[52,53] Han et al.[53,54] found that ankle proprioception scores were significantly and positively correlated with sport performance level in soccer. They argued that elite soccer