Proprioception in Orthopaedics, Sports Medicine and Rehabilitation

Defne Kaya
Baran Yosmaoglu
Mahmut Nedim Doral
Editors

Springer

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Preface

This book is dedicated to my father, Zekeriya Kaya, and to my mom, Ayse Kaya, with love. I have been extremely fortunate in my life to have parents who have shown me unconditional love and support.

A special word of thanks also goes to my dear professor, Mahmut Nedim Doral, for his contributions in my life and to be my icebreaker.

A special word of thanks also goes to my dear friend, Baran Yosmaoglu, for his contributions in the present book.

I am grateful for the love, encouragement, and tolerance of my love, Ceyhan Utlu, who has made all the difference in my life.

I am thankful for my sister, Duygu Kaya Yertutanol, the most precious gift in my life.

I wish to express a sincere thank you to all the authors who so graciously agreed to participate in the project.

I am also thankful for all who add value to my life.

Assoc Prof., İstanbul, Turkey, 2018 Defne Kaya

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About the Editors

Defne Kaya, Ph.D., M.Sc. She was born on December 23, 1976, in Cide/Kastamonu, Turkey. Dr. Kaya completed Master of Science program with her thesis entitled “Effectiveness of high voltage pulsed galvanic stimulation accompanying patellar taping on patellofemoral pain syndrome” in 2001. She worked in the Center for Rehabilitation Science of the University of Manchester for a postdoctoral project entitled “Optimizing physiotherapy in the treatment of patellofemoral pain syndrome” as a researcher for 6 months in 2007. In 2008, she completed her thesis entitled “Muscle strength, functional endurance, coordination, and proprioception in patellofemoral pain syndrome” and received her doctoral degree. Dr. Kaya worked on rehabilitation techniques for orthopedic problems and after orthopedic surgery when she worked as a research assistant from 1999 to 2008. She also worked on rehabilitation after medial patellofemoral ligament surgery in “Abteilung und Poliklinik für Sportorthopadie des Klinikum rechts der Isar der TUM” in September 2008. Dr. Kaya also worked as a researcher in Manchester University, Centre for Rehabilitation Science, Arthritis Research UK in November–December 2010 and September–November 2012.

In 2010, her and her colleagues’ paper, which was published in the journal *Sports Health*, titled “The effect of an exercise program in conjunction with short-period patellar taping on pain, electromyogram activity, and muscle strength in patellofemoral pain syndrome,” was selected as a suggestion paper by “Australian Sports Commission.”

In 2010, at the 10th Turkish Society of Sports Traumatology Arthroscopy and Knee Surgery Congress, her and her colleagues’ paper which was titled “Relation between the proprioception, muscle strength, and free-throw in professional basketball player” won the best presentation and young researcher award.

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She is an associate editor of the *Sports Injuries* published by Springer. She is also an editor of the book titled *Forgotten Sixth Sense: The Proprioception* published by OMICS Group.

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Mahmut Nedim Doral, M.D. is internationally recognized for his expertise in orthopedic sports medicine. He has authored over 150 scientific articles (more than 70 international and 100 national publications) in peer-reviewed journals and over 15 book chapters in internationally published books, and he acts as a referee in five international and four national journals. Recently, the book *Sports Injuries: Prevention, Diagnosis, Treatment and Rehabilitation* edited by Prof. Doral was published by Springer-Verlag. His major research interests are in sports injuries and rehabilitation, arthroscopic and endoscopic surgery, basic science research in tendon injuries, and knee arthroplasty since 1984. He was the Chairman of the Department of Orthopaedics and Traumatology at the Hacettepe University/Medical Faculty and the founder of the Department of Sports Medicine at the same University.

He has been the director of Hacettepe University Sports Medicine Center since 1995. He is the board member (2003–2009), program committee member and membership committee chairman (2007–2011), and archive committee member (2011–2019) of the International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS) and is on the scientific board of European Society of Sports Traumatology Knee Surgery and Arthroscopy (ESSKA). He also currently serves as Executive Council of Turkish National Olympic Committee.

Dr. Doral served as the President of Turkish Society of Orthopaedics and Traumatology (TOTBID) (2010–2011) and Turkish Arthroscopy, Knee Surgery and Sports Traumatology Society (2004–2006). He was the Past President of European Federation of Orthopaedic Sports Traumatology (EFOST) (2000–2003), Asia-Pacific Knee Society (APKS/Knee Section of APOA) (2004–2006), and Turkish Society of Sports Traumatology Arthroscopy and Knee Surgery (2002–2004); he is the elected president of APOA (Asia-Pacific Orthopaedic Society; 2018–2020). Prof. Doral is the Past Chief of Staff/Medical Committee Turkish Federation of National Basketball Team. He is the founder and current president of Turkish Society of Sports Traumatology. He was honored with distinguished visiting professor in the University of Pittsburgh School of Engineering in 2006 and Kentucky University in 2009.

Part I

Basics Knowledge of the Proprioception

1 Neurophysiology and Assessment of the Proprioception

Defne Kaya, Fatma Duygu Kaya Yertutanol, and Mahmut Calik

1.1 Introduction

Julius Caesar Scaliger was the first person who described the position-movement sensation as a "sense of locomotion" in 1557. After centuries in 1826, Charles Bell proposed that the information about the muscle's position were sent from muscles to brain which is in the opposite direction of motor comments. Bell's idea was noteworthy as explaining one of the first physiologic feedback mechanisms. In 1880, Henry Charlton Bastian suggested another term as "kinesthesia" instead of "muscle sense" to point out that afferent information was originating not only from muscles but also from joints, skin, and tendons. Alfred Goldscheider, a German neurologist, classified kinesthesia as muscle, tendon, and articular sensitivity in 1889. Finally in 1906, Charles Scott Sherrington introduced the terms "proprioception," "interoception," and "exteroception." "Exteroceptors" are sense organs such as eyes, ears, mouth, and skin that receive information from outside of the body, while "interoceptors" provide information about internal organs. On the other hand, "proprioception" is defined as awareness of movement and posture derived from muscle, tendon, and joint [1].

Movements of body parts are controlled by the functions of somatosensory and sensorimotor systems. Collective functioning of these systems is essential for an efficient proprioceptive sense. A *somatosensory system* consists of the sensory receptors, sensory neurons in the peripheral structures, and deeper neurons in the cortical structures. Receptors of somatosensory system are classified as thermoreceptors, photoreceptors, mechanoreceptors, and chemoreceptors. These receptors receive peripheral somesthetic (somatic) sense such as proprioceptive, tactile, thermal, and nociceptive information from skin and epithelia, skeletal muscles, bones and joints, internal organs, and cardiovascular system and transmit them to cortical structures. Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini's corpuscles which encapsulated mechanoreceptors are specialized to provide information to the central nervous system about touch, pressure, vibration, and cutaneous tension [2]. *Sensorimotor system* functions in a highly ordered fashion, where association cortex executes general commands and lower levels as motor neurons and muscles are interested in the

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details. This hierarchical arrangement enables higher level structures to focus on complex functions. The role of the hierarchically organized sensorimotor system is to generate motor output that is guided by sensory input and to learn the changes of the nature and locus of sensorimotor control [3]. On the other hand, sensorimotor system is part of the peripheral nervous system associated with the voluntary control of body movements via skeletal muscles. This system consists of efferent nerves which stimulate muscle contraction, including all non-sensory neurons connected with skeletal muscles and skin [4]. Sensory information influences the way we execute motor responses.

Purpose of this chapter is to introduce neurophysiological pathway of the proprioceptive sense. Proprioception (metaphorically is also called the "sixth sense"), kinesthesia, and neuromuscular control are often used interchangeably. Proprioceptive sense is more than just a feeling of movement, while proprioception represents the sense of awareness of joint position and kinesthesia describes the sensation of joint movement (see the summary of the proprioception in Fig. 1.1). Afferent signals from mechano- and cutaneous receptors are important to control joint movement (kinesthesia) and joint position (joint position sense). Massive proprioceptive input from specialized nerve endings originating from the muscles, fascia, tendons, ligaments, joints, and skin enters the dorsal horn of the spinal cord and is carried towards subcortical and cortical parts of the brain. Many neural pathways synapse at various levels of the nervous system, integrating all body position information to provide us with both a conscious and a nonconscious sense of where we are and how we are moving. We know where to place our extremities and how to move smoothly, accurately in different positions such as

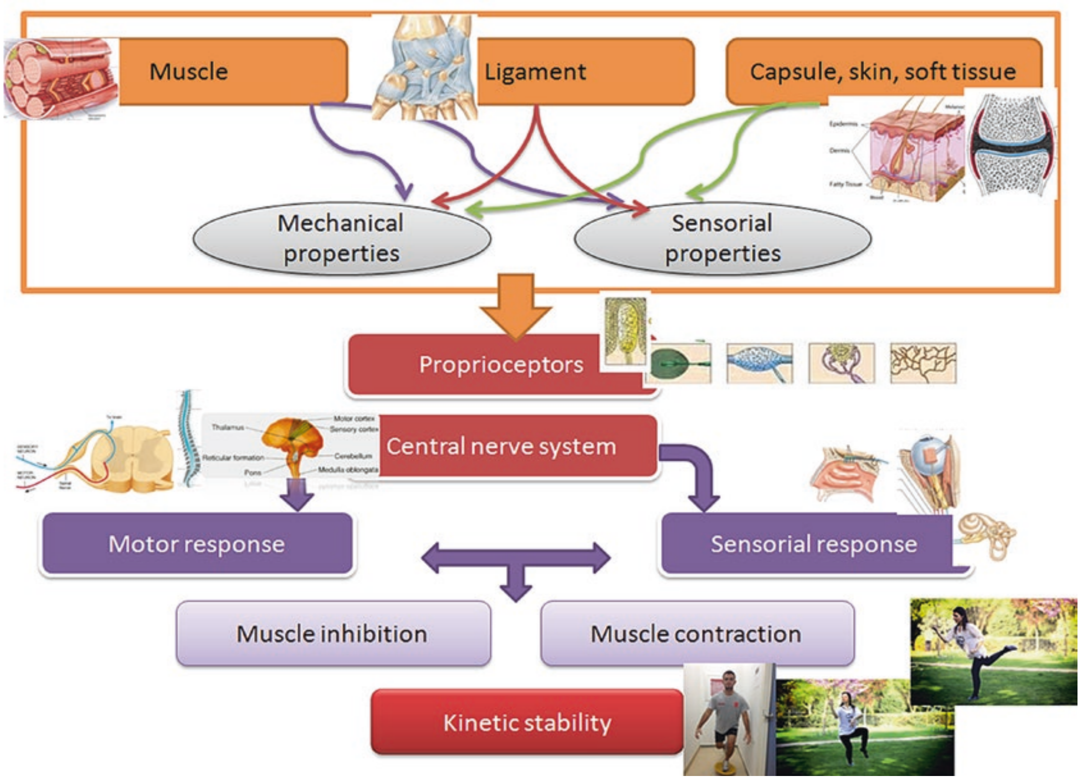

Fig. 1.1 Summary of the proprioception

standing, sliding, and turning with our eyes closed using proprioceptive or position-movement sense. In the case of an injury or a trauma, proprioceptors can be damaged. There is a discussion on whether proprioceptive deficits make individuals more vulnerable to injury or not [5]. Loss of this inner sense of timing and accuracy will lead to more severe injuries to occur and, of course, simple movements would take up an enormous amount of cognitive energy [5, 6].

1.2 Proprioceptive Receptors and Pathways

1.2.1 Peripheral Receptors and Pathway of Proprioception

Mechanoreceptors (proprioceptors) are also known as "receptors for self." Low-threshold mechanoreceptors such as muscle spindles, Golgi tendon organs, and joint mechanoreceptors receive sensory information and provide accurate complex body movements. Proprioceptors are also merged with the vestibular system to carry information about the position and motion of the head.

Muscle spindles are composed of approximately four to eight specialized intrafusal muscle fibers which are arranged in parallel with extrafusal fibers. The primary role of muscle spindles is to provide information about muscle length. Muscles that control fine movements contain more muscle spindles than do the muscles that control gross movements. Primary innervation is carried out by group I axons and the axon terminals are known as the primary sensory ending of the muscle spindle. Secondary innervation is provided by group II axons that innervate the nuclear chain fibers and give off a minor branch to the nuclear bag fibers. The intrafusal muscle fibers are innervated by γ motor neurons, which are derived from a pool of specialized neurons in the spinal cord. Unlike Golgi tendon organ, the muscle spindle doesn't relay signals through motor cortex; thus it isn't a feedback loop [7, 8].

Origin and insertion points of Golgi tendon organ (GTO), a sensory proprioceptor, are muscle fibers and tendons of skeletal muscles, respectively. Motor cortex inhibits muscle contraction in case of the excessive tension of the GTO. Muscle contractions which stimulate group Ib afferents lead the sensory terminals to compress by force. Group Ib sensory feedback generates spinal reflexes and supraspinal responses which control muscle contraction. Ib afferents synapse with interneurons that are within the spinal cord which also project to cerebellum and cerebral cortex. Golgi tendon organs are involved in cerebellar regulation of movement via dorsal and ventral spinocerebellar tracts [7, 8].

1.2.2 Ruffini Endings, Pacinian Corpuscles, and Golgi-Like Receptors Are Joint Mechanoreceptors

Ruffini endings, which are constantly reactive during joint motion, are slow-adapted and low-threshold receptors. Ruffini endings are very critical receptors in the regulation of stiffness and preparatory control of the muscles around the joint because they react to axial loading and tensile strain in the ligament [9]. *Pacinian corpuscles (deep pressure receptors)* (also known as lamellar corpuscles) are small, oval bodies that are found in deep layers of the skin and close to the GTOs. Pacinian corpuscles are rapidly adapted, high-threshold receptors and they are sensitive to mechanical disturbances such as joint acceleration/deceleration. They are also sensitive to quick movement and deep pressure [10]. Golgi-like ending, belonging to the same family as Ruffini ending, is silent during the rest and only active at the extremes of joint motion. Golgi-like receptors are important in monitoring tensile strain in the ligament during ultimate angles of joint motion [11].

Peripheral "ligamento-muscular reflexes" are also important for organizing peripheral proprioceptive reactions. These spinal reflexes are highly complex reactions that maintain adequate motor control of the joint [12]. Mono- and polysynaptic spinal reflexes between the ligaments in a joint and the muscles acting on that joint are well known and transmitted to the dorsal horn of the spinal cord [12, 13]. *Monosynaptic reflex* (such as a H-reflex), which is the fastest (within 20 ms after stimulation) and the simplest joint protective spinal reflex, can carry the peripheral information from skin, joints, ligaments, soft tissues, and tendons to the dorsal horn and directly stimulate the anterior horn for initial appropriate muscle contraction. As known, nerves carrying information from peripheral structures have the physiological properties necessary to compose initial joint protective reflexes. Delayed or earlier monosynaptic reflexes can cause uncontrolled joint motion and injury [14]. The efferent-muscular reaction can be caused by the *polysynaptic reflexes* with two or more interneurons [15]. The reflexes from cortical level are arranged by feed-forward inhibition, while reflexes from peripheral input are arranged by feed-back inhibition. Additionally, these inhibition systems are so critical to arrange the velocity, onset, and termination of motions. Spinal level reflexes can be controlled by muscle activity of the agonist and antagonist muscles which are influenced by feed-forward and feed-back inhibition systems [16].

1.3 Propriospinal Neurons and Pathway of Proprioception

Propriospinal system is a system that transmits motor inputs from supraspinal centers to motoneurons of spinal cord. Neurons of this system consist of spinal interneurons with their soma located in grey matter and their axons constitute white matter of spinal cord and terminate within it. These propriospinal neurons are settled rostral to motoneurons of spinal cord and can project to different locations like other spinal segments (intersegmental) or within that segment (intrasegmental). In contrary to the definition, it is important to note that some propriospinal neurons can also project to supraspinal areas [17].

Most of the studies related to propriospinal system come from studies on cats. Data coming from human studies are limited compared to animal studies. There are two basic kinds of propriospinal neurons: short axon propriospinal neurons and long axon propriospinal neurons [18]. Short axon propriospinal neurons project to within six spinal segments, whereas long axon propriospinal neurons reach beyond six spinal segments [18].

Short axon propriospinal projections may be classified as cervical and lumbosacral propriospinal projections, short thoracic propriospinal projections, and thoracic respiratory interneurons [18]. Cervical propriospinal projection which is also known as C3–C4 premotoneuronal system was defined in cats to mediate target-reaching movements [19]. The same system is thought to modulate corticospinal input to upper limb in humans [19]. On the other hand lumbosacral propriospinal projections transmit descending inputs to lower limb motoneurons. Short thoracic propriospinal projections were implicated for the control of axial muscles and thoracic respiratory interneurons were shown to receive respiratory drive to coordinate respiratory movements [18].

Long axon propriospinal projections are divided into long descending propriospinal tract projections, long ascending propriospinal tract projections, and upper cervical inspiratory interneurons [18]. Long descending propriospinal tract neurons are located in the cervical enlargement and project to the lumbosacral enlargement whereas long ascending propriospinal tract projections are located in the lumbosacral enlargement and project to the cervical enlargement. These neurons are thought to coordinate limb movements reciprocally during locomotion [17]. Upper cervical inspiratory interneurons project to intercostal and phrenic motoneurons and modulate inputs of brain stem to respiratory motoneurons [20].

In summary, the role of propriospinal system is to modulate descending and peripheral inputs for locomotion and autonomic and respiratory functions [18]. Thus, it functions as an integrating system for the inputs of cortical structures and the afferent feedback from limbs [19].

1.4 Cortical Receptors and Pathway of Proprioception

The excitatory and inhibitor synapses with afferent neurons help to carry peripheral proprioceptive information to higher cortical levels. Muscle, skin, ligament, and joint afferents and descending pathways are like a busy network of motorways. Somatosensorial information, which is sent from peripheral receptors via sensory nerves and tracts, is interpreted in the primary somatosensory area in the parietal lobe of cerebral cortex [2]. There are three neurons in somatosensory pathway. The first neuron is in dorsal root ganglion of spinal nerve. Ascending axons of the second neuron, which is in spinal cord, decussate to opposite side in the spinal cord. Axons of many of these neurons terminate in thalamus; others terminate in the reticular system or cerebellum. The third neuron is in thalamus and ends in postcentral gyrus of parietal lobe [21].

Corticospinal tract is the descending link between motor cortex and alfa and gamma motor neurons [22]. The kinesthetic information from muscle afferents of upper limbs is carried to cortex by *dorsal (posterior) columns*. The kinesthetic information from muscle afferents of lower limbs is carried to cortex by *Clarke's column* and *dorsal spinocerebellar tract*. The ascending pathways in spinal cord such as the *dorsal column medial lemniscal* and the *ventral spinothalamic pathways* carry information from body to brain and make a synapse in thalamus or reticular formation, before they reach cortex. The role of *ventral* and *dorsal spinocerebellar tracts*, which project to cerebellum, is to control posture and balance [21]. Cerebellum is responsible for coordinated motor movement. Cerebellum plans and modifies motor activities via *spinocerebellar tract*, which has a role in the regulation of gamma-MN drive to muscle spindles [23]. Spinocerebellar tract can carry peripheral information from skin, joint structures, and muscles to medulla, cerebellum, and dorsal column. Kinesthesia and joint position sense (independent of vision) are provided by intact and appropriate cerebellar function, which is influenced by peripheral information from muscle spindles and skin-stretch receptors [24] (see the summary of supraspinal reactions of proprioception in Fig. 1.2).

1.5 Peripheral Assessment Techniques of Proprioception

Proprioceptive measurements are performed to assess the quality of the proprioceptive function. Measurements are usually based on testing the quality of perception for some of the above-mentioned deep sense by CNS in various ways. However a highly appreciated by all researchers in proprioception measurements, practical, easily repeatable testing method that provides complete measurement of perception or response is not developed yet. The most frequent proprioception measurement methods following orthopedic injury/surgery/rehabilitation are joint position reproduction (JPR)—also known as joint position matching—threshold to detection of passive motion (TTDPM), and active movement extent discrimination assessment (AMEDA) [25]. Joint position sense, kinesthesia, and tension (force) sense are considered as subtitles of conscious proprioceptive sense and evaluated by using various techniques. Proprioceptive sense is usually evaluated both with and without body weight on the extremity. While performing the test using weight on the extremity, functional position is used; therefore proprioceptive information received due to compression would be more [26]. Joint position sense is tested in such a way that the patient actively and passively repeats the tested degree. Joint position sense test measures the certainty of repeatability of a particular position and performed actively and passively both open and closed kinetic chain positions. Repeating joint degrees are measured with direct (goniometer, potentiometer, video) and indirect

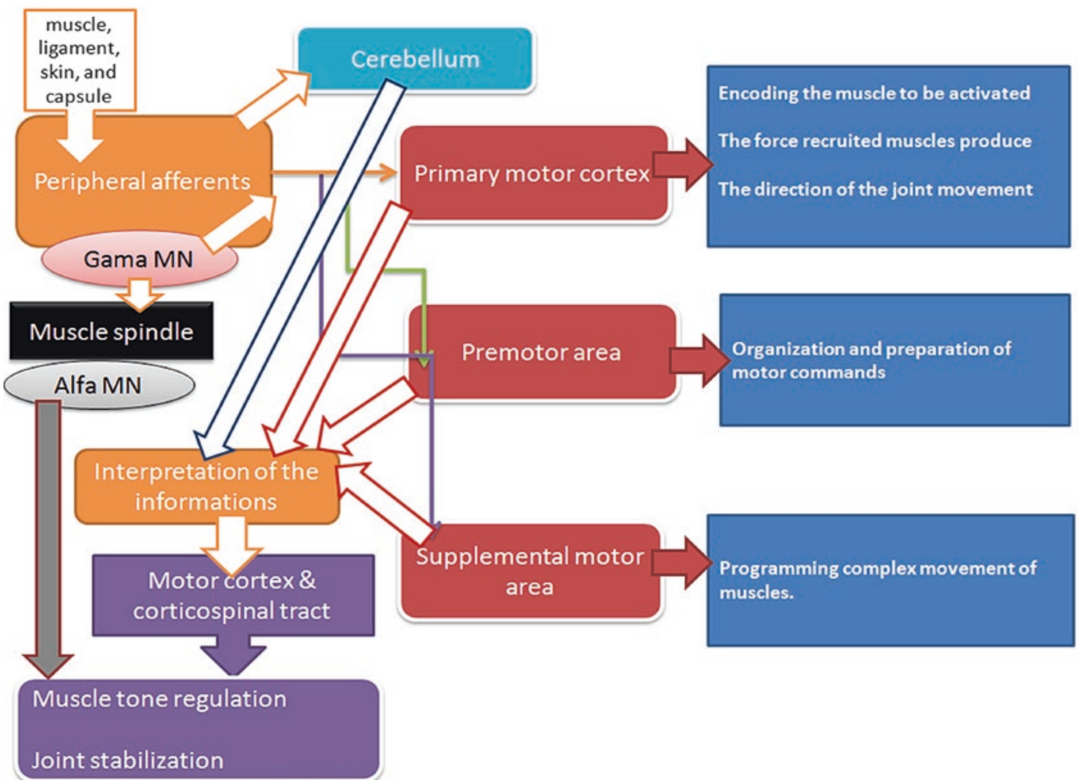

Fig. 1.2 Summary of the cortical pathways of the proprioception

(visual analog criterion) methods. Kinesthesia is evaluated by measuring threshold value for determining passive movement and more exclusively by finding out the threshold value of direction of movement. Accordingly not only the movement is defined but also the direction of the movement that generated. Tension (force) sense is measured by comparing the ability of people to repeat the magnitudes of torque that is produced under different circumstances by a group of muscles. To evaluate conscious proprioception, devices are built that follow various isokinetic dynamometers and electromagnetic trail. The objective of future studies is to verify conscious proprioceptive tension by measuring afferent pathway action potentials simultaneously (e.g., microneurography) and to compare the lack of sensorimotor control on dynamic joint stability and reduction in conscious proprioception [27]. Either rate of perception or tension of movement is measured in proprioception tests. Vibration sense is as much important as other deep senses in perceiving a joint's position, movement, and forces effecting on that joint. Basic studies showed that low-frequency vibration is perceived with Meissner's corpuscles and high-frequency vibration is perceived with Pacini corpuscles and thus is participated in the proprioceptive process [28]. Gilman [29] stated that the neural paths of position and vibration senses are same; however, mechanoreceptors that perceive these senses are different, in some of the diseases, and receptors of one sense can be kept healthy while receptors of the other sense are damaged. Vibration is explained in such a way that it affects both kinesthesia and position sense and participates in proprioceptive process directly [30, 31].

Key Knowledge

Active joint degree repetition is objectively evaluated using isokinetic system. Before undergoing the test, normal warming process should be performed, person should be blindfolded through the test, and distal part of its extremity should be put into pressure splint. The degree to be evaluated must be shown to the person eyes-open and blindfolded three times before the test. Six times repetition of each degree is necessary and the result will be their averages.

Passive joint degree repetition is objectively evaluated using isokinetic system. Before undergoing the test, normal warming process should be performed, person should be blindfolded through the test, and distal part of its extremity should be put into pressure splint. Data collection begins with the joint placed in a starting position of 0°. The test begins with the tester passively moving the test limb into a position of target (reference) angle and maintaining that position for 10 s. After 10 s of static positioning, the joint is moved back passively from the target angle to the starting position. The subject is asked to passively reproduce the previously presented test angle as a target (reference) angle. Six trials are performed on each joint, with a mean value in degrees of passive movement calculated. Passive movement speed should be at 0.50° or less. Angular displacement is recorded as the error in degrees between the target angle and the repositioned angle. The mean of the six trials for each tested condition is calculated to determine an average error in scores.

1.6 Cortical Assessment Techniques of Proprioception

Joint mechanoreceptors are negatively affected after injury and/or surgery. A few studies showed decreased somatosensory evoked potentials (SEPs) after anterior cruciate ligament injury and/or surgery [32, 33].

Electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) techniques were used to determine decreased proprioceptive sense after injury and/or surgery at cortical level in very limited number of studies [34, 35]. Using EEG and fMRI techniques, the pattern of whole-brain activity during motion of isolated joints of lower limb, the somatotopic organization of lower limb joint representations in primary sensorimotor cortex and anterior lobe of the cerebellum, and the degree of overlap between these lower limb joint activations should be investigated [34, 36]. Large prospective longitudinal studies are needed to detect the influence of cortical and peripheral proprioceptive sense after injury and/or surgery.

Practical Key Points

Example 1: Ankle Joint Position Sense Measurement Technique:

Proprioception level after endoscopically guided percutaneous Achilles tendon [37].

Ankle proprioception was defined as the ability to match reference ankle joint angles (the "target angle") without visual feedback. Joint position sense was measured by active angle reproduction (AAR) using a Biodex system 3 dynamometer (Biodex Corp., Shirley, NY, USA). The dynamometer was calibrated according to the manufacturer's instructions prior to each testing session; data were read from the on-screen goniometer. Patients sat upright with knee flexed to approximately 20, the seat back tilted 100, and their barefoot in a neutral position. They were asked to close their eyes during testing to eliminate visual input. For each repetition, the patients moved their limb to the target angle of either 10 for dorsiflexion or 15 for plantar flexion actively. These midrange angles were selected in an attempt to maximize sensory input from muscle proprioceptors. When patients felt they had reached the target angle, they activated the stop button and were not permitted to correct the angle. The angle was recorded from the on-screen goniometer; this process was repeated six times for each target angle. A total of six readings were taken, and the difference between the perceived angle and each of the target angles 10 for dorsiflexion or 15 for plantar flexion was noted as the absolute error and an average absolute error calculated for each trial.

Example 2: Knee Joint Position Sense Measurement Technique:

Is there a relationship between tracking ability, joint position sense, and functional level in patellofemoral pain syndrome? [38].

Joint position sense was measured by active reproduction test in the functional squat system. Functional squat system® is a valid tool assessing joint proprioception (2008, http://www.nhmi.net/validity_and_reliability_of_the_monitored_rehab.php) in clinical setting. Subjects were positioned in supine with the test knee flexed 90 while the opposite foot was resting on device. A load of 20% bodyweight as previously determined was applied during test performance. As they viewed the device monitor, subjects were instructed to keep the cursor on a defined pathway which provided them with continual knee position feedback. Following this, subjects were instructed to return to the start position of 90 knee flexion and attempt to replicate the reference knee position without visual feedback of the cursor. The difference in linear cursor position between the reference and reproduction trial was calculated by device software. This value represented error during active joint angle reproduction testing.

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