Chapter

Proprioception and Clinical Correlation

Pinar Gelener, Gözde İyigün and Ramadan Özmanevra

Abstract

Proprioception is the sense of position or the motion of the limbs and body in the absence of vision. It is a complex system having both conscious and unconscious components involving peripheral and central pathways. The complexity of sensorimotor systems requires deep knowledge of anatomy and physiology to analyze and localize the symptoms and the signs of the patients. Joint sense and vibration sense examination is an important component of physical examination. This chapter consists anatomy, motor control, postural control related to proprioception with neurologic clinical correlation and also the information about the changes of proprioception after orthopedic surgeries and discuss with the available literature.

Keywords: proprioception, neurology, orthopedics

1. Introduction

1.1 Anatomy

Proprioception was first described by Sir Charles Bell in 1830s as sixth sense coming from Latin word proprius meaning "one's own" and perception "perceiving one's own self" [1]. Proprioception is generally defined as either the sense of position or the motion of the limbs and body in the absence of vision [2]. Limb position is a static sense, whereas limb motion is a dynamic sense [3]. It is described as the most important sensorial modality for the internal representation of body map providing static and dynamic proprioceptive systems [4].

Proprioception is a complex system having both conscious and unconscious components involving peripheral and central pathways. The proprioceptive sensations arise from the deeper tissues. The main receptors are muscle spindles, tendons, Ruffini endings in joint capsules ligaments and Pacinian corpuscles reacting pressure, tension, stretching or contraction. The cutaneous receptors of the skin also contribute to joint position and motion sense especially at digits, elbow and knee. The term kinesthesia is generally used to describe the conscious awareness of the body or limb position in space [1, 5–7]. Conscious proprioceptive impulses elongate along large and myelinated fibers from the peripheral nerves into the dorsal root ganglion of spinal cord (first order neurons) and then via the medial division of the posterior root, via posterior white columns of fasciculi gracilis and cuneatus and ascend to the nuclei gracilis and cuneatus in the lower medulla. Axons of the second-order neuron decussate as internal arcuate fibers (second order neurons), and then ascend in the medial lemniscus to the contralateral somatosensory region of thalamus (**Figure 1**) [2, 5].

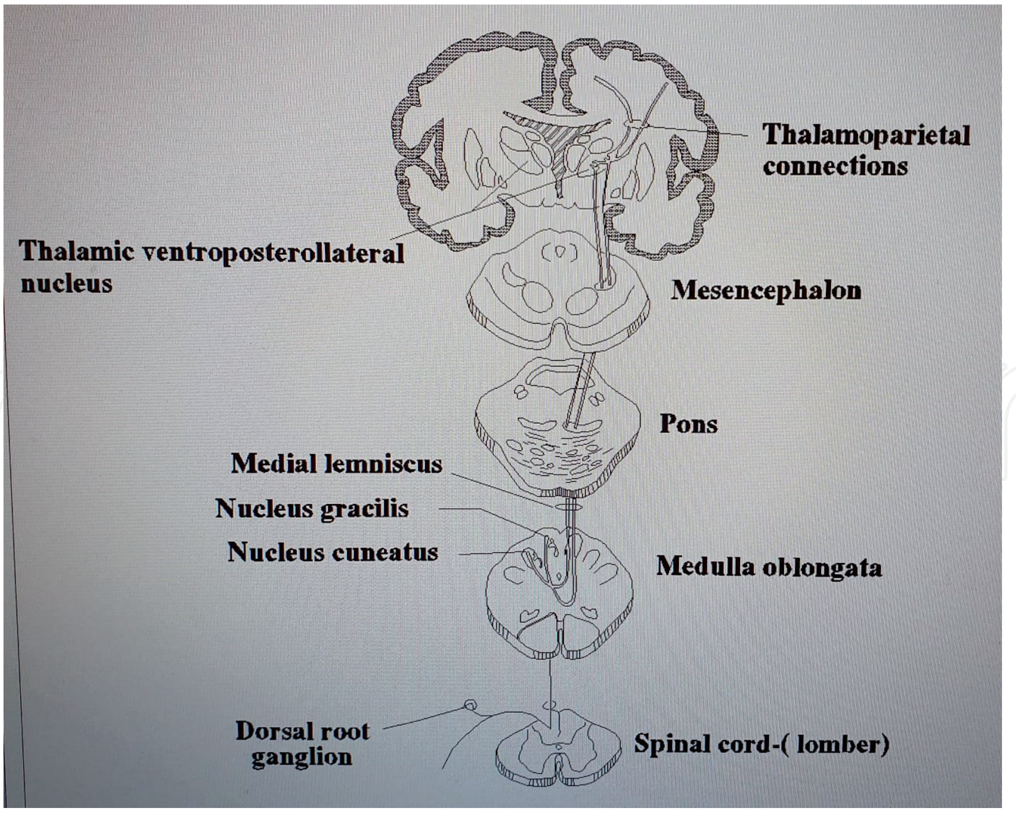

Figure 1.
Neuroanatomic pathway adopted from DeJong's the neurologic examination.

The main pathway for proprioceptive information is via the dorsal column medial lemniscal, posterior and anterior spinocerebellar tracts and spinoreticular tracts [6, 7].

There is a high density of complex spindles in deeper cervical muscles particularly in the intermediate columns, acting as neck prorioceptive receptors. This system is important for head and neck position sense together with the high density muscle spindles of sub-occipital triange. The density of muscle spindles is higher in the upper cervical spine when compared with the lower cervial and cervico-thoracic and thoraco-lumbar junctions [8]. Neck proprioception plays an important role in limb coordination and body-scheme representation [8]. Proprioceptive impulses from the head and neck are supplied by cranial nerves [5].

Contralateral primary and secondary sensorimotor cortex, supplementary motor area and bilateral inferior parietal lobes and basal ganglia (especially nigrostriatal pathways, striatal neurons and putamen) are involved in processing proprioceptive information during passive movement [9, 10]. The cerebellum contributes to proprioception only during movement [3]. Especially deep medial fastigial nucleus of cerebellum converges vestibular and neck proprioceptive sensory signals describing body's movement in space [11, 12].

1.2 Proprioception and motor control

The sensorimotor system, defined as the sensory, motor, and central integration, is a crucial and intricate component of the motor control system [13]. Motor control is a complex and dynamic process based on the selective integration of sensory information from multiple sources, motor commands, and motor output [13, 14]. There are specific unique roles associated with each sensory source (i.e., somatosensory, visual, vestibular) that cannot be compensated fully with each other [14, 15]. The environment is experienced through sensory systems: exteroception (e.g., sight, hearing, touch), interoception (e.g., arousal, pain, visceral sensations, muscular sensations), and proprioception (e.g., sense of position, motion, and force), which all required for successful motor control [16, 17]. During a task-oriented activity, motor adaptation, defined as a process of modifying the movement based on error feedback [18], skills are needed to cope with the changes occurring in the *external* and *internal environment* [2]. Motor adaptation is stimulated with sensorial triggers by using both feedback (reactive: adjust ongoing motor behavior) and feedforward (preparatory: pre-planning and anticipating the motor sequence from the previous experience) mechanism. Proprioceptive information, from proprioceptors found in muscle, tendon, ligament, capsule, skin, and fascial layers, plays an integral role in motor control and considered as multifold [14].

The role of proprioceptive information in motor control can be divided into two categories: *external environment* (even vs. uneven ground) and *internal environment* (carrying a load on shoulders vs. hands below knuckle height). The motor programs often need to be adjusted to accommodate unexpected perturbations or changes in the *external environment*. Although the source of this information is usually associated mainly with visual input, there are many situations where proprioceptive input is the fastest and/or most accurate. Proprioception is necessary during motion execution to update feedforward commands derived from the visual image [14]. Attention to environmental constraints is also required because dealing with complex environments often requires behavioral flexibility to maintain postural balance [19]. Secondly, the central nervous system needs an updated body schema of the biomechanical and spatial properties of body parts to plan and modify *internally generated* motor commands [20]. Before and during a motor command, the motor control system must consider the current and changing positions of the respective joints to account for the complex mechanical interactions within the musculoskeletal system components [14]. Additionally, proprioception is important after movement to compare the actual movement and intended movement, besides the predicted movement derived from the efference copies (corollary discharge: copying of motor commands based on past events) of motor commands, which has an essential role in motor learning to update the internal forward model of motor command [21].

1.3 Proprioception and postural control

During the execution of all motor tasks, proprioception is required to prepare, maintain, and restore the stability of both the entire body (postural equilibrium) and the segments (joint stability) [14, 15]. Postural control, defined as controlling the position of the body regarding the task in the environment, involves neural control of "postural equilibrium" and "postural orientation". Postural equilibrium consists of the coordination of sensory and motor strategies to maintain balance by controlling the body's center of mass (COM) over its base of support (BOS) to maintain postural stability during both intrinsic (self-initiated) and extrinsic (externally triggered) disturbances. The postural equilibrium controls stability during both static (i.e., quiet standing) and dynamic (i.e., walking and reaching) situations. Postural orientation involves positioning body alignment with respect to gravity, the support surface, visual environment, and other sensory reference frames [22].

Postural control is considered as a complex motor skill derived from the interaction of multiple sensorimotor processes, which are; biomechanical constraints (i.e., BOS, degrees of freedom, strength, limits of stability), movement strategies (i.e., reactive, anticipatory, voluntary), sensory strategies (i.e., sensory integration, sensory re-weighting), orientation in space (i.e., perception of visional verticality, perception of postural verticality), control of dynamics (i.e., gait, proactive), cognitive processing (i.e., attention, learning, reaction time), experience and practice [23]. Impairment of the proprioceptive sensation can disrupt any of these six resources, which contributes to postural control (**Figure 2**). "*Sensory strategies*" are one of the most critical issues to discuss. Sensory information from somatosensory (tactile sense and proprioception), visual and vestibular systems must be integrated to interpret complex sensory environments for achieving postural control. Depending on the environmental conditions, the relative contribution of each sensory system changes, which is referred to as "sensory re-weighting" [24]. Healthy persons rely on somatosensory (70%), vision (10%), and vestibular (20%) information when standing on a stable surface in a well-lit environment (13). On the other hand, when standing on an unstable surface, due to decreased dependence on surface somatosensory inputs for postural orientation, they need to increase sensory weighting to vestibular and visual information [25]. The dynamic regulation or re-weighting of sensory cues is essential for maintaining postural stability when moving between different environments requiring distinct sensorial systems, such as different surfaces (i.e., walking on the sidewalk, walking on grass) or different lighting (i.e., moving in a well-lit room, moving in a dark room) [23]. The interplay between these three sensory modalities is critical for accurate estimates of self-motion and postural control [26].

Besides different sensory cues, different mechanical conditions provide significant advantages to humans for maintaining upright standing [27]. Decreased proprioception could lead to "*biomechanical constraints*" such as abnormal joint biomechanics and decreased muscle strength [28, 29], leading to postural dyscontrol. The "*control of dynamics*" is defined as the ability to perceive body segments relative to one another to stabilize the COM. Maintaining COM requires input from multiple sensory systems, sensorial re-weighting, and multisensory integration to calculate body state, including the COM and heading [30]. "*Movement strategies*" (i.e., postural

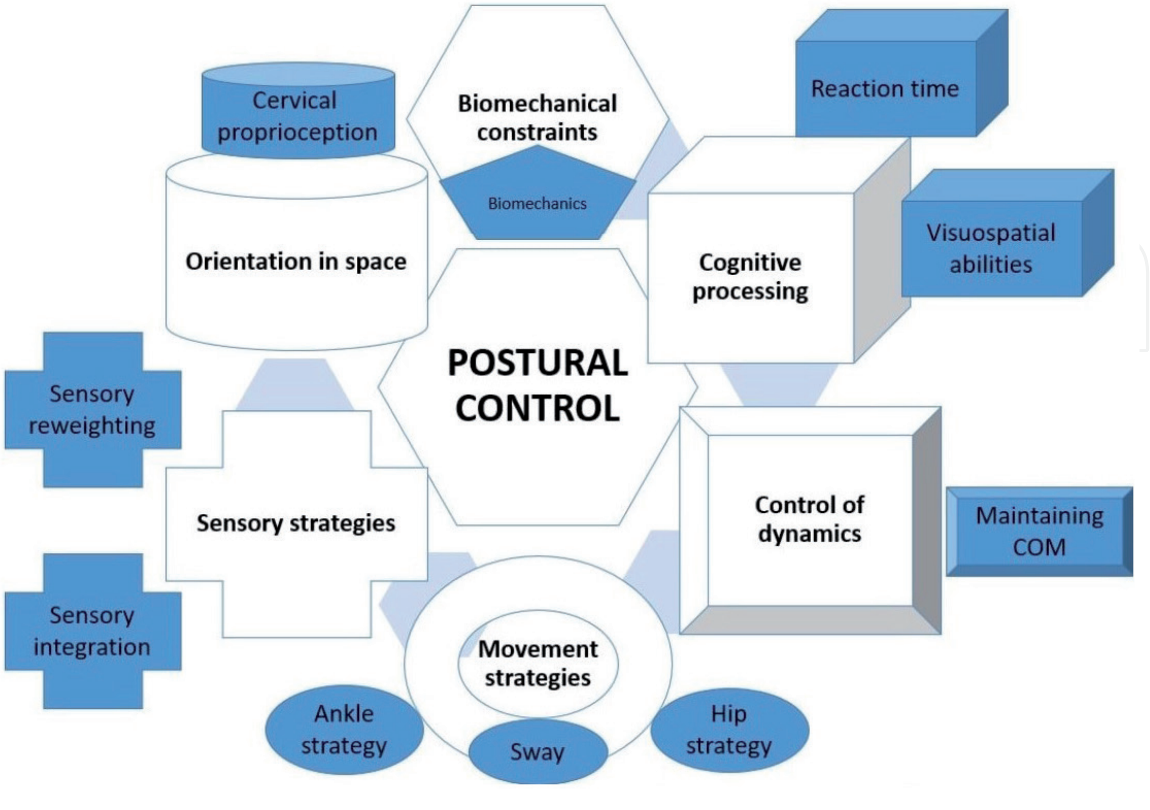

Figure 2.
Adapted from the framework of the six important resources required for postural control system by Horak, 2006 [23], the contribution of proprioception sensation to postural control.

sway, ankle strategy, hip strategy) can be used to return the body to equilibrium in a stance position [23]. Without proprioceptive input from the ankle and knee, ankle muscle responses are delayed suggesting that lower leg balance correcting responses are triggered by hip and, possibly, trunk proprioceptive inputs. Especially hip muscle proprioceptive inputs, considered critical for automatic balance correcting responses [31]. Additionally, cervical proprioception is of particular importance for "*orientation in space*". Neck muscle inflow has effects on the perception of body orientation and motion. Prolonged, intense proprioceptive input from neck muscles can induce persistent influences on self-motion perception and cognitive body representation [32]. The loss of proprioception could also impact the "*cognitive processing*" specifically the reaction time, and other factors such as attention, memory, and visuospatial abilities may contribute to spatial cognitive skills (**Figure 2**) [23].

2. Clinical implications and evaluation of proprioception

The loss of proprioceptive afferents may affect the control of muscle tone, disrupts postural reflexes, and severely impairs spatial and temporal aspects of movement [33]. Proprioceptive impairments are associated with various neurological conditions such as stroke [34], Parkinson's disease [35], peripheral neuropathy [36], as well as orthopedic conditions such as low back pain [37], neck pain [38], sports injuries like chronic ankle instability [39], ACL injuries [40], post-operatively such as mastectomy [41], knee arthroplasty [42], and aging [43]. Considering the importance of proprioception for motor control, a detailed evaluation of proprioceptive sense and application of treatment approaches focusing on training the proprioceptive sense is important for restoring motor function. Proprioception can be measured by using specific and non-specific tests in clinical practice.

Specific Tests of Proprioception: assess an individual's status regarding the joint position sense and kinesthesia [21]. *Joint position sense* tests assess precision or accuracy in repositioning the joint at a predetermined target angle and can be measured as active joint position detection (AJPD) [e.g., position matching task, position copying task] and passive joint position detection (PJPD) [e.g., thumb finding test, dual-joint position test] [44]. *Kinesthesia* tests assess the ability to perceive joint movement. For evaluating the perceptual aspect of proprioception, psychophysical thresholds represent the gold standard [33]. These tests are usually performed passively and can be measured by using passive motion detection threshold (PMDT) and passive motion direction discrimination (PMDD) [e.g., distal proprioception test, Rivermead Assessment of Somatosensory Perception] [44].

Non-specific Tests of Proprioception: for determining the contribution of proprioceptive signals on balance control, functional balance tests can be used to provide an estimate of potential proprioceptive disturbances [33]. These tests involve all body and other sensory and motor functions; therefore, they are considered non-specific tests of proprioception [21]. *Balance tests* can be modified to challenge proprioception, such as unilateral/bilateral stance with eyes open/closed, different supporting surfaces (i.e., stable or unstable), and with/without perturbations [44, 45]. *Stereognosis* and *skilled motor function tests* are important as they indicate the contribution of proprioceptive system in the performance of many activities of daily living [46].

3. Neurologic correlation

The complexity of sensorimotor systems requires deep knowledge of anatomy and physiology to analyze and localize the symptoms and the signs of the patients.

Joint sense and vibration sense examination is an important component of neurological examination.

The classic diseases causing sensory ataxia are tabes dorsalis, polyneuropathies (especially involving large fibers), dorsal root ganglionopathies and subacute combined degeneration. With parietal lobe lesion, position sense is often impaired and vibration preserved [5]. Vibratory sensation may also be impaired in lesions of the peripheral nerves, plexopathies, radiculopathies, dorsal root ganglion, posterior columns and medial lemniscus. In patients with peripheral neuropathies, vibration sensation is lost in the lower extremities first. Impaired vibration from posterior column disease is more likely to be uniform at all sites in the involved extremities. In spinal cord diseases, detecting a "level" of vibration sensory (segmental demarcation) loss over the spinous processes is crucial for diagnosis [5]. In patients with diabetic neuropathy, the decline in proprioceptive function may be caused by impairment in muscle spindle function and or the spindle receptors itself [47].

In patients with hereditary sensory and autonomic neuropathy type III patients (Riley-Day Syndrome, familial dysautonomia) ataxic gait is explained by poor proprioceptive acuity at the knee joint [48]. In mitochondrial ataxias sensory ataxia (which classically include gait ataxia worsened by loss of visual fixation) is due to the involvement of proprioception, secondary to peripheral neuropathy or neuronopathy [49]. In patients following whiplash type injuries involving soft tissues of cervical spine leads to proprioceptive deficits affecting head and position sense. Also in patients with chronic whiplash associated disorders are reported to have balance and dizziness problems, head and eye movement impairments reflecting mismatch od afferent input from the proprioceptive, visual and vestibular systems [8, 50]. Lesions of the dorsal columns impairs sensation of touch, vibration and proprioception in the ipsilateral side of the body below the injury level [51]. In patients with non-specific low back pain, postural control is impaired during standing and slow performance movements. This is due to an altered use of ankle compared to back proprioception related activity in right primary motor cortex and frontoparietal cortex [52]. Brainstem lesions resemble those in spinal cord disease as it selectively involves spinothalamic tract or medial lemniscus causing contralateral loss of position sense and vibration sense [5].

Neglect is a condition in which patients loose self-spatial awareness opposite to the damaged site of the brain. It is proposed that it is associated with the lesions of the dorsal stream causing dysfunction of proprioceptive space which is encoded in the bilateral parietal cortex [53]. Loss in the position sense may cause pseudochoreoathetosis as well. This abnormal involuntary, spontaneous movements are restricted to the parts with proprioceptive sensory loss. It is proposed that failure to integrate cortical proprioceptive sensory inputs in striatum may explain this situation [5, 54].

There are experimental evidence of proprioception impairments in Parkinson's disease. Parkinsonian gait is affected by the involvement of lower limb proprioceptive deficits as well as the involvement contralateral somatosensory and premotor lateral cortices and posterior cingulate cortex and basal ganglia and bilateral prefrontal cortex [10, 55, 56]. It was also shown that conscious perception of kinaesthetic stimuli is impaired in Parkinson's disease as cerebro-basal loops are not intact [9].

Weeks and colleagues showed that patients with cerebellar damage had reduced dynamic proprioceptive acuity which was also parallel to their motor deficits [3]. Diseases of the primary somatosensory cortex do not generally produce sensory symptoms but deteriorate fine and delicate manipulations in the contralateral part depending on position sense [2, 5]. Many patients with stroke experience proprioceptive deficits. Recovery of proprioception increases in the chronic phase [57, 58]. In study by Pope it was shown that proprioceptive input from the neck also may change cerebellar output affecting M1 plasticity [59]. In the study of Vidoni and colleagues preserved motor learning after stroke was related to the degree of proprioceptive deficit suggesting the relation between proprioceptive perception from muscle spindles and motor learning and central neuroplasticity [58, 60].

4. Proprioception after orthopedic surgeries

Studies on changes in joint proprioception after orthopedic surgeries are available in the literature. This section consists of the information in the literature about our five major joints.

4.1 Knee joint

Knee proprioception is necessary to achieve normal joint coordination during movement as well as providing joint stabilization [61, 62]. The anterior cruciate ligament (ACL), posterior cruciate ligament, collateral ligaments and menisci contribute to proprioception with the help of proprioceptors they have [63, 64]. The mechanoreceptors of the cruciate ligaments, together with the mechanoreceptors of the joint capsule, transmit information about the extension and flexion of the knee joint to the brain [65].

The ACL is the most important ligament involved in knee mechanical and neuromuscular stability. It contributes to proprioception in joint movement. However, the ACL is the most frequently injured ligament. After ACL rupture, knee proprioception is disrupted [66, 67].

Various autografts and allografts are used for ACL reconstruction. Patellar tendon or hamstring tendons may be preferred in patients using autografts. In addition, different techniques and materials are used. However, there is no gold standard in graft and technique selection [68]. In order for ACL reconstruction to be successful, not only mechanical but also neuromuscular stability is required. Neuromuscular stability depends on obtaining proprioception [69]. ACL injury leads to degradation of mechanoreceptors and a histologic study revealed that free nerve endings disappear after 1 year [70]. The effectiveness of ACL reconstruction in regaining proprioception has been tried to be revealed by some studies [71–74]. While some studies argue that ACL reconstruction is not sufficient to restore joint position [71–73], some studies advocate the adverse opinion [74]. The lack of a test to distinguish about whether the proprioception is derived from the soft tissues around the knee and capsule or from mechanoreceptors on ACL prevents to reach a certain decision about the mechanoreceptors of ACL [75].

Even after total knee arthroplasty, the contribution of the soft tissues around the knee to proprioception continues. In order to take advantage of this effect and ensure satisfactory outcomes in these patients, the soft tissue and gap must be well adjusted. Unicompartmental replacement protecting the ACL may be more advantageous in not reducing proprioception due to the proprioceptive effect of ACL. Also Ishii et al. [76] conclude that balance is improved after the postoperative period in bilateral total knee arthroplasty. It is stated that the first 6-week period is the critical period for adaptation time and proprioceptive loss after total knee replacement, and a new pattern in the knee load distribution occurs with postoperative rehabilitation [77].

4.2 Hip joint

Loss of proprioception, balance, sensation as joint position and kinesthetic are frequently observed in patients with knee osteoarthritis [78, 79]. Shakoor et al. [80] described significant sensory deficits associated with hip osteoarthritis, and these deficiencies involved both upper and lower limbs. The mechanism for this remains unclear; however, it has been suggested that there may be neurological feedback mechanisms or a inherent generalized neurological defect [78].

The greatest portion of mechanoreceptors and free nerve endings and highest concentration of pain receptors are located in the anterosuperior, posterosuperior and anterolateral labrum, respectively [81, 82].

There is no satisfactory information about proprioception impairment after surgeries due to hip pathologies. In the literature on the relationship between arthroplasty and proprioception, there are studies related to the knee rather than the hip. Interestingly, Ishii et al. [83] found no difference in proprioceptive responses among participants in the total hip arthroplasty, hemiarthroplasty and healthy control groups. They thought that the mechanoreceptors in the muscles, tendons and ligaments were responsible for joint proprioception rather than the intracapsular structures. While capsular receptors play a secondary role, muscle receptors play a primary role in hip proprioception. Therefore, it has been suggested that proprioception does not decrease after surgery, despite the capsule being removed during arthroplasty [84].

The effects of FAI and labral tear treatments on proprioception are not well known, but due to their proprioceptive properties, hip musculotendinous and capsuloligamentous tissues contribute to lower limb posture and stabilization through neuromuscular control. Therefore, preserving proprioceptive tissues as much as possible will prevent lower extremity injuries in arthroscopy operations.

4.3 Ankle joint

Ankle injuries are in the first place in sports-related injuries and lateral ankle sprains constitute the majority of this [85]. Unfortunately, many of these acute injuries can become chronic [86, 87]. Training, fatigue, and ankle injuries can affect ankle proprioception. Joint position sense, peroneal reaction time, EMG evaluation of peroneal muscles, and balance tests are tools to evaluate proprioception before and after ankle injuries or surgeries.

There are two important anatomical structures that provide proprioception and are located around the foot and ankle. Superior and inferior extensor retinaculum act as a pulley protecting tendons close to bony structures. The lateral ankle complex is the other anatomical structure with proprioceptive properties [88, 89]. Both acute and chronic injuries of the ankle can predispose the proprioceptors of the ankle. The differentiation in proprioception after these injuries were presented in the literature. While Vries et al. [90] stated that there was no difference between chronic ankle injury, acute trauma and healthy control groups, there are studies suggested that proprioception after acute inversion injuries and chronic ankle injuries are decreased [91–93]. Recovery of the proprioception is crucial after ankle injuries to maintain balance control. In order to achieve this, rehabilitation should not be neglected, especially after lateral ankle sprains.

A study conducted by Conti et al. [94] found no difference in proprioception between operated and non-operated side in total ankle arthroplasty. However, ankle arthroplasty has the worst outcome in terms of proprioception and balance compared to total hip and knee arthroplasty [95].

4.4 Shoulder joint

Some studies have revealed Pacinian corpuscles and Golgi tendon organ with mechanoreceptors in the shoulder [96, 97]. However, they discovered that while there are free nerve endings in the labrum and subacromial bursa, these structures do not contain mechanoreceptors. It is also thought that the supraspinatus muscle has more receptors than the infraspinatus muscle contains [98].

The pathological conditions of the shoulder joint can affect shoulder proprioception. Surgical shoulder diseases include rotator cuff tears, subcacromial pathologies, biceps tendon diseases and instabilities. Studies comparing pre- and post-surgical proprioception in the shoulder joint are not sufficient. In a study conducted by Aydın et al. [99], it was revealed that there was no difference in terms of proprioception between surgically treated and non-surgically treated shoulders in cases of instability. Duzgun et al. [100] stated a rapid recovery in shoulder joint proprioception after rotator cuff surgery as their experience.

Shoulder arthroplasty is thought to negatively affect proprioception. It has been stated that intervention to the subscapularis muscle and glenohumeral ligaments during shoulder arthroplasty may be effective in this decrease in proprioception [101, 102].

4.5 Elbow joint

Soft tissue damage is significant in elbow arthroplasty. Both flexor and extensor muscles are affected, collateral ligaments are released and capsule is removed. Therefore, the proprioceptive tissues as like skin, capsule, muscle and tendons are damaged. Despite the role of proprioception is still not well-established, one study was found an impairment in proprioception after total elbow arthroplasty [103].

In conclusion, proprioception may be adversely affected after joint surgeries. It should definitely be included in the rehabilitation program considering this situation. Proprioception seems to be an important factor for gaining balance and gait speed, especially after arthroplasties in the lower extremity.

Conflict of interest

The authors declare no conflict of interest.

Author details

Pinar Gelener[1*], Gözde İyigün[2] and Ramadan Özmanevra[3]

1 Department of Neurology, Faculty of Medicine, University of Kyrenia, Kyrenia, Northern Cyprus, Mersin 10 via Turkey

2 Department of Physiotherapy and Rehabilitation, Faculty of Health Sciences, Eastern Mediterranean University, Famagusta, Northern Cyprus, Mersin 10 via Turkey

3 Department of Orthopedics and Traumatology, Faculty of Medicine, University of Kyrenia, Kyrenia, Northern Cyprus, Mersin 10 via Turkey

*Address all correspondence to: drpinargelener@gmail.com

References

[1] Hillier S, Immink M, Thewlis D. Assessing proprioception: a systematic review of possibilities. Neurorehabilitation and neural repair. 2015;29(10):933-949. DOI:10.1177/1545968315573055

[2] Gilman S. Joint position sense and vibration sense: anatomical organisation and assessment. Journal of Neurology, Neurosurgery & Psychiatry.2002;73:473-477.

[3] Weeks HM, Therrien AS, Bastian AJ. The cerebellum contributes to proprioception during motion. Journal of Neurophysiology.2017;118(2):693-702. DOI:10.1152/jn.00417.2016

[4] Cignetti F, Caudron S, Vaugoyeau M, Assaiante C. Body schema disturbance in adolescence: from proprioceptive integration to the perception of human movement. Journal of Motor Learning and Development.2013;1(3):49-58. DOI: 10.1123/jmld.1.3.49

[5] Campbell WW, DeJong RN. DeJong's the neurologic examination. Lippincott Williams & Wilkins; 2005.

[6] Bosco G, Poppele RE. Proprioception from a spinocerebellar perspective. Physiological reviews. 2001;81(2):539-568.

[7] MacKinnon CD. Sensorimotor anatomy of gait, balance, and falls. Handb Clin Neurol. 2018;159, 3-26. DOI: 10.1016/B978-0-444-63916-5.00001-X.

[8] Armstrong B, McNair P, Taylor D. Head and neck position sense. Sports medicine. 2008;38(2):101-117. DOI: 10.2165/00007256-200838020-00002

[9] Maschke M, Gomez CM, Tuite PJ, Konczak J. Dysfunction of the basal ganglia, but not the cerebellum, impairs kinaesthesia. Brain. 2003;126(10):2312-2322. DOI: 10.1093/brain/awg230

[10] Ribeiro L, Bizarro L, Oliveira A. Proprioceptive deficits in Parkinson's disease: from clinical data to animal experimentation. Psychology & Neuroscience. 2011;4(2):235-244. DOI:10.3922/j.psns.2011.2.009

[11] Luan H, Gdowski MJ, Newlands SD, Gdowski GT. Convergence of vestibular and neck proprioceptive sensory signals in the cerebellar interpositus. Journal of Neuroscience. 2013;16;33(3):1198-210. DOI: 10.1523/JNEUROSCI.3460-12.2013

[12] Brooks JX, Cullen KE. Multimodal integration in rostral fastigial nucleus provides an estimate of body movement. Journal of Neuroscience. 2009;29(34):10499-10511. DOI:10.1523/JNEUROSCI.1937-09.2009

[13] Lephart SM, Riemann BL, Fu FH. Introduction to the sensorimotor system. In: Lephart S M, Fu F H, Editors. Proprioception and Neuromuscular Control in Joint Stability. Human Kinetics; Champaign; 2000:37-51.

[14] Riemann BL, Lephart SM. The sensorimotor system, Part II: The role of proprioception in motor control and functional joint stability. J Athl Train. 2002;37(1):80-84. DOI:10.1016/j.jconhyd.2010.08.009

[15] Riemann BL, Lephart SM. The sensorimotor system, Part I: The physiologic basis of functional joint stability. J Athl Train. 2002;37(1):71-79.

[16] Valori I, McKenna-Plumley PE, Bayramova R, Callegher CZ, Altoè G, Farroni T. Proprioceptive accuracy in Immersive Virtual Reality: A developmental perspective. Senju A, ed. PLoS One. 2020;15(1):e0222253. DOI:10.1371/journal.pone.0222253

[17] Marshall AC, Gentsch A, Schütz-Bosbach S. The interaction between interoceptive and action states within a framework of predictive coding. Front Psychol. 2018;9(FEB):180. DOI:10.3389/fpsyg.2018.00180

[18] Martin TA, Keating JG, Goodkin HP, Bastian AJ, Thach WT. Throwing while looking through prisms II. Specificity and storage of multiple gaze-throw calibrations. Brain. 1996;119(Pt 4):1199-1211. DOI:10.1093/brain/119.4.1199

[19] Dakin CJ, Bolton DAE. Forecast or fall: Prediction's importance to postural control. Front Neurol. 2018;9:924. DOI:10.3389/fneur.2018.00924

[20] Maravita A, Spence C, Driver J. Multisensory integration and the body schema: Close to hand and within reach. Curr Biol. 2003;13(13):R531-R539. DOI:10.1016/S0960-9822(03)00449-4

[21] Röijezon U, Clark NC, Treleaven J. Proprioception in musculoskeletal rehabilitation: Part 1: Basic science and principles of assessment and clinical interventions. Man Ther. 2015;20(3):368-377. DOI:10.1016/j.math.2015.01.008

[22] Horak FB. Postural Control. In: Binder M.D., Hirokawa N., Windhorst U. (Eds). Encyclopedia of Neuroscience. Springer, Berlin, Heidelberg. ; 2009:3212-3219. DOI:10.1007/978-3-540-29678-2_4708

[23] Horak FB. Postural orientation and equilibrium: What do we need to know about neural control of balance to prevent falls? Age Ageing. 2006;35(SUPPL.2):7-11. DOI:10.1093/ageing/afl077

[24] Nashner L, Berthoz A. Visual contribution to rapid motor responses during postural control. Brain Res. 1978:403-407. DOI:10.1016/0006-8993(78)90291-3

[25] Peterka RJ. Sensorimotor integration in human postural control. J Neurophysiol. 2002;88(3):1097-1118. DOI:10.1152/jn.2002.88.3.1097

[26] Hwang S, Agada P, Kiemel T, Jeka JJ. Dynamic reweighting of three modalities for sensor fusion. PLoS One. 2014;9(1):e88132. DOI:10.1371/journal.pone.0088132

[27] Peterka RJ. Comparison of Human and Humanoid Robot Control of Upright Stance. J Physiol Paris. 2009;103(5):149-158. DOI:10.1016/j.jphysparis.2009.08.001

[28] Ito T, Sakai Y, Ito Y, Yamazaki K, Morita Y. Association Between Back Muscle Strength and Proprioception or Mechanoreceptor Control Strategy in Postural Balance in Elderly Adults with Lumbar Spondylosis. Healthcare. 2020;8(1):58. DOI:10.3390/healthcare8010058

[29] Ribeiro F, Oliveir J. Factors Influencing Proprioception: What do They Reveal? In: Biomechanics in Applications. InTech; 2011. DOI:10.5772/20335

[30] Chiba R, Takakusaki K, Ota J, Yozu A, Haga N. Human upright posture control models based on multisensory inputs; in fast and slow dynamics. Neurosci Res. 2016;104:96-104. DOI:10.1016/j.neures.2015.12.002

[31] Bloem B, Allum JHJ, Carpenter M, Verschuuren J, Honegger F. Triggering of balance corrections and compensatory strategies in a patient with total leg proprioceptive loss. Exp Brain Res. 2002;142(1):91-107. DOI:10.1007/s00221-001-0926-3

[32] Pettorossi VE, Schieppati M. Neck Proprioception Shapes Body Orientation and Perception of Motion. Front Hum Neurosci. 2014;8:1-13. DOI:10.3389/fnhum.2014.00895

[33] Aman JE, Elangovan N, Yeh IL, Konczak J. The effectiveness of proprioceptive training for improving motor function: A systematic review. Front Hum Neurosci. 2015;8(JAN):1-18. DOI:10.3389/fnhum.2014.01075

[34] Rand D. Proprioception deficits in chronic stroke—Upper extremity function and daily living. PLoS One. 2018;13(3):e0195043. DOI:10.1371/journal.pone.0195043

[35] Teasdale H, Preston E, Waddington G. Proprioception of the Ankle is Impaired in People with Parkinson's Disease. Mov Disord Clin Pract. 2017;4(4):524-528. DOI:10.1002/mdc3.12464

[36] Li L, Zhang S, Dobson J. The contribution of small and large sensory afferents to postural control in patients with peripheral neuropathy. J Sport Heal Sci. 2019;8(3):218-227. DOI:10.1016/j.jshs.2018.09.010

[37] Tong MH, Mousavi SJ, Kiers H, Ferreira P, Refshauge K, van Dieën J. Is There a Relationship Between Lumbar Proprioception and Low Back Pain? A Systematic Review With Meta-Analysis. Arch Phys Med Rehabil. 2017;98(1):120-136. DOI:10.1016/j.apmr.2016.05.016

[38] Stanton TR, Leake HB, Chalmers KJ, Moseley GL. Evidence of impaired proprioception in chronic, idiopathic neck pain: Systematic review and meta-analysis. Phys Ther. 2016;96:876-887. DOI:10.2522/ptj.20150241

[39] Xue X, Ma T, Li Q, Song Y, Hua Y. Chronic ankle instability is associated with proprioception deficits: A systematic review with meta-analysis. J Sport Heal Sci. 2020;00:1-10. DOI:10.1016/j.jshs.2020.09.014

[40] Kim HJ, Lee JH, Lee DH. Proprioception in Patients with Anterior Cruciate Ligament Tears: A Meta-analysis Comparing Injured and Uninjured Limbs. Am J Sports Med. 2017;45(12):2916-2922. DOI:10.1177/0363546516682231

[41] Zabit F, Iyigun G. A comparison of physical characteristics, functions and quality of life between breast cancer survivor women who had a mastectomy and healthy women. J Back Musculoskelet Rehabil. 2019;32(6):937-945. DOI:10.3233/BMR-181362

[42] Bragonzoni L, Rovini E, Barone G, Cavallo F, Zaffagnini S, Benedetti MG. How proprioception changes before and after total knee arthroplasty: A systematic review. Gait Posture. 2019;72:1-11. DOI:10.1016/j.gaitpost.2019.05.005

[43] Ribeiro F, Oliveira J. Aging effects on joint proprioception: The role of physical activity in proprioception preservation. Eur Rev Aging Phys Act. 2007;4:71-76. DOI:10.1007/s11556-007-0026-x

[44] Hillier S, Immink M, Thewlis D. Assessing Proprioception: A Systematic Review of Possibilities. Neurorehabil Neural Repair. 2015;29(10):933-949. DOI:10.1177/1545968315573055

[45] Clark NC, Ulrik R. Proprioception in musculoskeletal rehabilitation. Part 2 : Clinical assessment and intervention. Man Ther. 2015;20:378-387. DOI:10.1016/j.math.2015.01.009

[46] Stillman BC. Making sense of proprioception: The meaning of proprioception, kinaesthesia and related terms. Physiotherapy. 2002;88:667-676. DOI:10.1016/S0031-9406(05)60109-5

[47] Van Deursen RW, Sanchez MM, Ulbrecht JS, Cavanagh PR. The role of muscle spindles in ankle movement perception in human subjects with diabetic neuropathy. Experimental brain research. 1998 Apr 1;120(1):1-8.

[48] Bennell KL, Hinman RS, Metcalf BR, Crossley KM, Buchbinder R, Smith M, McColl G. Relationship of knee joint proprioception to pain and disability in individuals with knee osteoarthritis. Journal of orthopaedic research. 2003 Sep;21(5):792-797. DOI:10.1016/S0736-0266(03)00054-8

[49] Vernon HJ, Bindoff LA. Mitochondrial ataxias. InHandbook of clinical neurology 2018 Jan 1 (Vol. 155, pp. 129-141). Elsevier. DOI:10.1016/B978-0-444-64189-2.00009-3.

[50] Treleaven J, Peterson G, Ludvigsson ML, Kammerlind AS, Peolsson A. Balance, dizziness and proprioception in patients with chronic whiplash associated disorders complaining of dizziness: a prospective randomized study comparing three exercise programs. Manual therapy. 2016 Apr 1;22:122-130. DOI:10.1016/j.math.2015.10.017

[51] Wirz M, van Hedel HJ. Balance, gait, and falls in spinal cord injury. InHandbook of clinical neurology 2018 Jan 1 (Vol. 159, pp. 367-384). Elsevier. DOI:10.1016/B978-0-444-63916-5.00024-0.

[52] Goossens N, Janssens L, Caeyenberghs K, Albouy G, Brumagne S. Differences in brain processing of proprioception related to postural control in patients with recurrent non-specific low back pain and healthy controls. NeuroImage: Clinical. 2019 Jan 1;23:101881. DOI:10.1016/j.nicl.2019.101881

[53] Vakalopoulos C. Unilateral neglect: a theory of proprioceptive space of a stimulus as determined by the cerebellar component of motor efference copy (and is autism a special case of neglect). Medical hypotheses. 2007 Jan 1;68(3):574-600. DOI:10.1016/j.mehy.2006.08.013.

[54] Sharp FR, Rando TA, Greenberg SA, Brown L, Sagar SM. Pseudochoreoathetosis: movements associated with loss of proprioception. Archives of neurology. 1994 Nov 1;51(11):1103-1109. DOI:10.1001/archneur.1994.00540230041010

[55] Jacobs JV, Horak FB. Abnormal proprioceptive-motor integration contributes to hypometric postural responses of subjects with Parkinson's disease. Neuroscience. 2006 Jan 1;141(2):999-1009. DOI:10.1016/j.neuroscience.2006.04.014

[56] Keijsers NL, Admiraal MA, Cools AR, Bloem BR, Gielen CC. Differential progression of proprioceptive and visual information processing deficits in Parkinson's disease. European Journal of Neuroscience. 2005 Jan;21(1):239-248. DOI:10.1111/j.1460-9568.2004.03840.x

[57] Bowden JL, Lin GG, McNulty PA. The prevalence and magnitude of impaired cutaneous sensation across the hand in the chronic period post-stroke. PloS one. 2014 Aug 14;9(8):e104153. DOI:10.1371/journal.pone.0104153.

[58] Tashiro S, Mizuno K, Kawakami M, Takahashi O, Nakamura T, Suda M, Haruyama K, Otaka Y, Tsuji T, Liu M. Neuromuscular electrical stimulation-enhanced rehabilitation is associated with not only motor but also somatosensory cortical plasticity in chronic stroke patients: an interventional study. Therapeutic advances in chronic disease. DOI:10:2040622319889259.

[59] Popa T, Hubsch C, James P, Richard A, Russo M, Pradeep S, Krishan S, Roze E, Meunier S, Kishore A. Abnormal cerebellar processing of the neck proprioceptive information drives dysfunctions in cervical dystonia. Scientific reports. 2018 Feb 2;8(1):1-0. DOI:10.1038/s41598-018-20510-1

[60] Vidoni ED, Boyd LA. Preserved motor learning after stroke is related

to the degree of proprioceptive deficit. Behavioral and Brain Functions. 2009 Dec 1;5(1):36. DOI:10.1186/1744-9081-5-36.

[61] Pai YC, Rymer WZ, Chang RW, et al. Effect of age and osteoarthritis on knee proprioception. Arthritis Rheum. 1997;40:2260-2265. DOI: 10.1002/art.1780401223.

[62] Abelew TA, Miller MD, Cope TC, et al. Local loss of proprioception results in disruption of interjoint coordination during locomotion in the cat. J Neurophysiol. 2000;84:2704-2714. DOI: 10.1152/jn.2000.84.5.2709.

[63] Solomonow M, Krogsgaard M. Sensorimotor control of knee stability. A review. Scand J Med Sci Sports. 2001;11:64-80. DOI: 10.1034/j.1600-0838.2001.011002064.x.

[64] Jennings AG. A proprioceptive role for the anterior cruciate ligament: a review of the literature. J Orthop Rheumatol. 1994;7:3-13.

[65] Lephart SM, Riemann BL, Fu FH. Introduction to the sensorimotor system. In: Lephart SM, Fu FH, editors. Proprioception and neuromuscular control in joint stability. Champaign, IL: Human Kinetics;2000.

[66] Anders JO, Venbrocks RA, Weinberg M. Proprioceptive skills and functional outcome after anterior cruciate ligament reconstruction with a bone-tendon-bone graft. Int Orthop. 2008;32:627-633. DOI: 10.1007/s00264-007-0381-2

[67] Angoules AG, Mavrogenis AF, Dimitriou R, et al. Knee proprioception following ACL reconstruction: a prospective trial comparing hamstrings with bone-patellar tendon-bone autograft. Knee. 2011;18:76-82. DOI: 10.1016/j.knee.2010.01.009.

[68] Yosmaoglu HB, Baltacı G, Kaya D, et al. Comparison of functional outcomes of two anterior cruciate ligament reconstruction methods with hamstring tendon graft. Acta Orthop Traumatol Turc. 2011;45:240-247. DOI: 10.3944/AOTT.2011.2402.

[69] Krogsgaard MR, Dyhre-Poulsen P, Fischer-Rasmussen T. Cruciate ligament reflexes. J Electromyogr Kinesiol. 2002;12:177-182. DOI: 10.1016/s1050-6411(02)00018-4.

[70] Denti M, Monteleone M, Berardi A, et al. Anterior cruciate ligament mechanoreceptors. Histologic studies on lesions and reconstruction. Clin Orthop Relat Res. 1994;308:29-32. PMID: 7955696

[71] MacDonald PB, Hedden D, Pacin O, et al. Proprioception in anterior cruciate ligament-deficient and reconstructed knees. Am J Sports Med. 1996;24:774-8. DOI: 10.1177/036354659602400612

[72] Yosmaoglu HB, Baltacı G, Kaya D, et al. Tracking ability, motor coordination, and functional determinants after anterior cruciate ligament reconstruction. J Sport Rehabil. 2011;20:207-218. DOI: 10.1123/jsr.20.2.207

[73] Yosmaoglu HB, Baltacı G, Ozer H, et al. Effects of additional gracilis tendon harvest on muscle torque, motor coordination, and knee laxity in ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2011;19:1287-1292. DOI: 10.1007/s00167-011-1412-5

[74] Reider B, Arcand MA, Diehl LH, et al. Proprioception of the knee before and after anterior cruciate ligament reconstruction. Arthroscopy. 2003;19:2-12. DOI: 10.1053/jars.2003.50006.

[75] Hogervorst T, Brand R. Mechanoreceptors in joint function. J Bone Joint Surg Am. 1998;80:1365-1378. DOI: 10.2106/00004623-199809000-00018.

[76] Ishii Y, Noguchi H, Takeda M, Sato J, Kishimoto Y, Toyabe S-I. Changes of body balance before and after total knee arthroplasty in patients who suffered from bilateral knee osteoarthritis. J Orthop Sci. 2013;18(5):727-732. DOI: 10.1007/s00776-013-0430-1.

[77] Thewlis D, Hillier S, Hobbs SJ, Richards J. Preoperative asymmetry in load distribution during quite stance persist following total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2014;22(3):609-614. DOI: 10.1007/s00167-013-2616-7.

[78] Hurley MV. The role of muscle weakness in the pathogenesis of osteoarthritis. Rheum Dis Clin N Am. 1999;25:283-298.

[79] Nyland J, Wera J, Henzman C, et al. Preserving knee function following osteoarthritis diagnosis: a sustainability theory and social ecology clinical commentary. Phys Ther Sport. 2015;16:3-9. DOI: 10.1016/j.ptsp.2014.07.003

[80] Shakoor N, Lee KJ, Fott LF, et al. Generalized vibratory deficits in osteoarthritis of the hip. Arth Rheum. 2008;59:1237-1240. DOI: 10.1002/art.24004

[81] Alzaharani A, Bali K, Gudena R, et al. The innervation of the human acetabular labrum and hip joint: an anatomic study. BMC Musculoskelet Disord. 2014;15:41. DOI:10.1186/1471-2474-15-41.

[82] [82]Haversath M, Hanke J, Landgraeber S, et al. The distribution of nociceptive innervation in the painful hip: a histological investigation. Bone Joint. 2013;J95:770-776. DOI: 10.1302/0301-620X.95B6.30262.

[83] Ishii Y, Tojo T, Terajima K, et al. Intracapsular components do not change hip proprioception. J Bone Joint Surg Br. 1999;81:345-348. DOI: 10.1302/0301-620x.81b2.9104.

[84] Nallegowda M, Singh U, Bhan S, Wadhwa S, Handa G, Dwivedi SN. Balance and gait in total hip replacement: a pilot study. Am J Phys Med Rehabil. 2003;82(9):669-677. DOI: 10.1097/01.PHM.0000083664.30871.C8.

[85] Janssen KW, Kamper SJ. Ankle taping and bracing for proprioception. Br J Sports Med. 2013;47:527-528. DOI: 10.1136/bjsports-2012-091836

[86] Karlsson J, Lansinger O. Lateral instability of the ankle joint. Clin Orthop Relat Res. 1992;276:253-261. PMID: 1537162

[87] Kerkhoffs GM, Handoll HH, de Bie R, Rowe BH, Struijs PA. Surgical versus conservative treatment for acute injuries of the lateral ligament complex of the ankle in adults. Cochrane Database Syst Rev. 2007;(2):CD000380. DOI: 10.1002/14651858.CD000380.pub2.

[88] Li HY, Zheng JJ, Zhang J, Cai YH, Hua YH, Chen SY. The improvement of postural control in patients with mechanical ankle instability after lateral ankleligaments reconstruction. Knee Surg Sports Traumatol Arthrosc. 2016;24(4):1081-1085. DOI: 10.1007/s00167-015-3660-2.

[89] Hertel J. Sensorimotor deficits with ankle sprains and chronic ankle instability. Clin Sports Med. 2008;27:353-70. DOI: 10.1016/j.csm.2008.03.006.

[90] Vries S, Kingma I, Blankevoort L, van Dijk CN. Difference in balance measures between patients with chronic ankle instability and patients after an acute ankle inversion trauma. Knee Surg Sports Traumatol Arthrosc. 2010;18(5):601-606. DOI: 10.1007/s00167-010-1097-1.

[91] Hertel J. Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. J Athl Train. 2002;37:364-375. PMID: 12937557

[92] Docherty CL, Valovich McLeod TC, Shultz SJ.Postural control deficits in participants with functional ankle instability as measured by the balance error scoring system. Clin J Sport Med. 2006;16:203-208. DOI: 10.1097/00042752-200605000-00003.

[93] Jerosch J, Hoffstetter I, Bork H, Bischof M. The influence of orthoses on the proprioception of the ankle joint. Knee Surg Sports Traumatol Arthrosc. 1995;3:39-46. DOI: 10.1007/BF01553524.

[94] Conti SF, Dazen D, Stewart G, Green A, Martin R, Kuxhaus L, et al. Proprioception after total ankle arthroplasty. Foot Ankle Int. 2008;29(11):1069-1073. DOI: 10.3113/FAI.2008.1069.

[95] Butler RJ, Thiele RAR, Barnes CL, Bolognesi MP, Queen RM. Unipedal balance is affected by lower extremity joint arthroplasty procedure 1 year following surgery. J Arthroplasty. 2015;30(2):286-289. DOI: 10.1016/j.arth.2014.08.031.

[96] Vangness CT Jr, Ennis M, Taylor JG, Atkinson R. Neural anatomy of the glenohumeral ligaments, labrum, and subacromial bursa. Arthroscopy. 1995;11(2):180-184. DOI: 10.1016/0749-8063(95)90064-0.

[97] Ide K, Shirai Y, Ito H, Ito H. Sensory nerve supply in the human subacromial bursa. J Shoulder Elb Surg. 1996;5:371-382. DOI: 10.1016/s1058-2746(96)80069-3.

[98] Windhorst U. Muscle proprioceptive feedback and spinal networks. Brain Res Bull. 2007;73:155-202. DOI: 10.1016/j.brainresbull.2007.03.010.

[99] Aydin T, Yildiz Y, Yanmiş I, Yildiz C, Kalyon TA. Shoulder proprioception: a comparison between shoulder joint in healthy and surgically repaired shoulders. Arch Orthop Trauma Surg. 2001;121(7):422-425. DOI: 10.1007/s004020000245.

[100] Duzgun, I., & Turhan, E. (2017). Proprioception After Shoulder Injury, Surgery, and Rehabilitation. Proprioception in Orthopaedics, Sports Medicine and Rehabilitation, 35-45. DOI:10.1007/978-3-319-66640-2_4.

[101] Maier MW, Niklasch M, Dreher T, Wolf SI, Zeifang F, Loew M, Kasten P. Proprioception 3 years after shoulder arthroplasty in 3D motion analysis: a prospective study. Arch Orthop Trauma Surg. 2012;132(7):1003-1010. DOI: 10.1007/s00402-012-1495-6

[102] Kasten P, Maier M, Retting O, Raiss P, Wolf S, Loew M. Proprioception in total, hemi- and reverse shoulder arthroplasty in 3D motion analyses: a prospective study. Int Orthop. 2009;33(6):1641-1647. DOI: 10.1007/s00264-008-0666-0.

[103] Lubiatowski P, Olczak I, Lisiewicz E, Ogrodowicz P, Bręborowicz M, Romanowski L. Elbow joint position sense after total elbow arthroplasty. J Shoulder Elbow Surg. 2014;23(5):693-700. DOI: 10.1016/j.jse.2014.01.016.