Proprioception: The Forgotten Sixth Sense

Chapter: Muscle, Tendon, Ligament Tear and Proprioception

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Abstract

Mechanoreceptors in healthy muscles, ligaments and tendons procure the sensation of the joint movement, joint position and stability. Loss of mechanoreceptors not only causes mechanical instability, but also leads to a disturbance in the neuromuscular control due to the loss of mechanoreceptors. The purpose of this review is to explore the anatomy of mechanoreceptors in soft musculoskeletal tissues and to analyze their function both in normal and pathological conditions.

Introduction

The term proprioception was first used by Sherrington in 1906 [1]. Proprioception is the sensation of the joint movement and joint position. This allows us to perceive the space around us and react rapidly in changing circumstances [2]. Knowledge about position and movement of the limbs and trunk is due to afferent stimuli arising from sensory receptors. These sensors are called mechanoreceptors. Several classifications are reported for mechanoreceptors but the most has been published by Freeman and Wyke (Table 1).

Type	Morphology	Parent Nerves	Function
I	Globular corpuscles in clusters. Thinly encapsulated	Small myelinated fibres	Static, dynamic; low threshold, slowly adapting.
II	Conical corpuscles, thickly encapsulated	Medium myelinated fibres	Dynamic receptors; low threshold, rapidly adapting.
III	Fusiform corpuscles, thinly encapsulated	Large myelinated fibres	Dynamic receptors; high threshold, very slowly adapting.
IV	Free nerve endings	Very small myelinated. Unmyelinated.	Pain receptors; high threshold, non-adapting.

Table 1: Classification of Nerve Endings according to Freeman and Wyke [3].

Ligamentous Mechanoreceptors

Research has shown that four types of nerve endings can be listed in ligaments: Ruffini corpuscles, Paccini corpuscles, Golgi tendon organ-like endings and free nerve endings [4]. These four types of receptors were also found in the fibrous joint capsule. The function of these receptors is not completely clear. Ruffini endings are type I endings. They are thinly encapsulated, globular corpuscles, 100x40μ and are found of clusters of three to six corpuscles, mainly in the superficial layers of the fibrous joint capsule. Their afferent nerve fibers are small, myelinated and measure 6-9μ in diameter. They are a low-threshold, slowly adapting receptors that respond to mechanical stresses.

Ruffini endings are intertwined with collagen fibers and they seem to be activated by the displacement of the fibers. Collagen fibers run axially and pass through both ends of the corpuscle to merge with the collagen in the surrounding region of the tissue. Ruffini corpuscles are both static and dynamic mechanoreceptors which are able to signal static joint position, changes in intra-articular pressure as well as movements direction, amplitude and velocity [4,5].

Pacinian corpuscles are classified as type II articular receptors, they are thickly encapsulated, conical corpuscles 280x120μ, found in clusters of two to four corpuscles (Figure 1). Their afferent nerves are medium size, myelinated and measure 9-12μ in diameter. These are dynamic, rapidly adapting mechanoreceptors with a low threshold. They are inactive on immobile joints, though becoming active at the acceleration and deceleration [6].

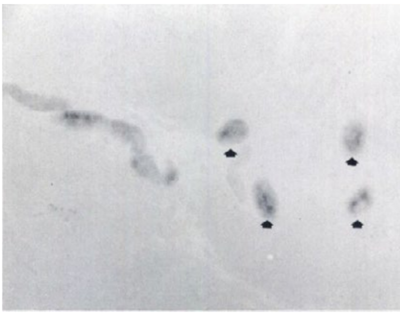

Figure 1: Mechanoreceptors Type II [6].

Golgi tendon organs endings are type III mechanoreceptors, they have an high threshold and are slowly adapting (Figure 1). They are inactive in immobile joint and it has been suggested that they measure the ligaments tension. They have been discovered in the cruciate ligaments, medial collateral ligament, the medial patellar ligament. Finally, free nerve endings are the articular nociceptors endings or the mechanoreceptors type IV [6] (Figure 2).

Figure 2: Mechanoreceptors Type II (hollow arrows) and III (black arrows) [6].

Tendinous Mechanoreceptors

Golgi tendon organ-like endings have been found in tendons. They lie at the myo-aponeurotic and mio-tendinous aponeurotic junctions of the mammalian skeletal muscles. A similar receptor is present also in capsular joint (Figure 3). They are thinly encapsuated, fusiform corpuscles, 600x100μ, located mostly on the surfaces of intrinsic and extrinsic ligaments of joints. They afferent fibers are large and myelinated, with a diameter of 13-17μ. They are connected to collagen bundles in continuity with tendon or aponeurosis, the other side is connected with 5-25 muscle fibers. Stimulus response suggest they are high-threshold, slowly adapting mechanoreceptors that are completely inactive in immobile joints. They become active when joints are at the extreme of their ranges of movement and considerable stresses are generated in the joint ligaments [4,6].

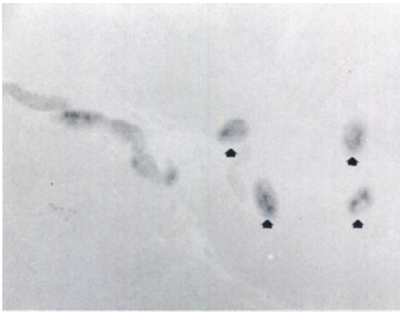

Figure 3: Mechanoreceptors Type IV [6].

Muscle Mechanoreceptors

Golgi tendon organs co-work with another mechanoreceptor: the muscle spindle. This is one of the most complex receptor in the human body, after the eye and the ear. Indeed muscle spindles are the most innervated receptors, with afferent and efferent fibers. They are aligned parallel to the muscle fibers and they primarily detect changes in the length and the speed of muscles [7].

As aforementioned last sensors we have to consider the tendon receptors. These are free nerve endings that are categorized as Type IV articular receptors. Their afferent fibers are very small in size: the ones myelinated have a diameter of 2-5μ; instead those unmyelinated have a diameter less than 2μ. These endings are high-threshold, non-adapting pain receptors [4].

Mechanoreceptors function as transducers devices converting a signal in one form of energy to another one (i.e. the physical stimulus of tension into a specific nerve signal). This nerve signal is not simply a single discharge, but rather a repetitive discharge when the receptor is excited above its threshold by a stimulus. Greater is the stimulus, more rapid is the firing rate from mechanoreceptor. Therefore, the summation of receptor discharges forms a frequency-modulated code that the central nervous system uses to analyze joint position, motion and acceleration [8]. In addition to providing specific information, mechanoreceptors demonstrate adaptability or a decrease in frequency of nerve impulses upon continued excitation by a receptor. This is the phenomenon of mechanoreceptor adaptation to a repeated stimulus. In this way the body avoids central system overload due to too many signals at the same time. The transduction of mechanical stimuli into electrical responses is essential for audition, kinesthesis, proprioception and automatic sensation of pressure and volume. Seems that Pacinian corpuscles and Golgi tendon organs are more represented than Ruffini endings in ligaments, both Pacinian corpuscles and Golgi tendon organs are physiologically reflexogenic. Pacinian corpuscles discharge at the onset or cessation of movement and are involved in quick movements, this afferent feedback to the central nervous system would have a stabilizing effect on the joints. Golgi tendon organs are found in ligaments, myo-tendinous and myo-aponeuotic junctions of mammalian skeletal muscle. Their discharges are responsible for tension and joint position; thus they are also responsible for joint stabilization [4,9].

Healing of Muscle Mechanoreceptor

Few reports focused the healing of mechanoreceptors. Recently Scott and Panesar denervates the muscle peroneus tertius of cats for 20-24 weeks and repeating the lesion every 3 weeks to avoid the axons to reach the muscle. After this period the nerve was allowed to recover for 12 weeks. They showed that muscle spindle afferents reinnervate their original ending sites with the spindle after a nerve injury but the afferents that had been regenerated are smaller than the control group. Muscle spindle had a higher discharge rates than the regenerated so the study state that denervation and reinnervation process causes increasing of the peacemaker threshold.

In contrast Haftel and coworkers showed that not all the regenerated afferences where able to restore a pathway to central nervous system. In a rat model the lateral gastrocnemius-soleus was cutted and sutured. The afferents showed that an inital burst firing was smaller for reinnervate receptors (60% vs 77% healthy group), even if this difference was not significant according to authors. Moreover there were some differences in muscle spindle responses to stretch, showing that reinnervated afferences had an increased length in threshold, probably due to an incomplete recovery of gamma-moto neurons drive to reinnervated muscle spindles.

Furthermore there was a loss of stretch reflex for regenerated afferences, basically due to a reduced percentage of innervated receptors after the nerve tear.

Partially these receptors may be supplied by the wrong classes of afferences, and as last mechanism, a pre-synaptic or a post-synaptic inhibition suppressing the moto neurons. Deletion of reflex stretch brings to an important alteration of the muscle proprioception; consequently this loss of information leads to a problem while executing contraction of the muscle fibers and to alterate control of limbs in the space [10].

Healing of Tendon Mechanoreceptors

Scott and coworkers [11] examined Golgi tendon organs after nerve injury in a peroneus tertius muscle cat model. The dynamic response of the Golgi tendon organs is made physiologically by two components: an initial peak and a second main component showing correlation between tension rate and discharge frequency. The fascicle of the nerve involving the peroneus tertius was crushed in the first group, while the nerve was cut and immediately sutured in the second group. During first part of the healing motor units had to come to a full recovery. Speed contraction and absolute tension were not fully restored yet. Almost all receptors were reinnervated. Six weeks after the nerve crush 85 muscle units were isolated and were recorded 62 activations of the Golgi tendon organs (40% were phasic only, falling to 19% at 10 weeks). In the second group the recovery was much poorer. 72 activations from the muscle units were recorded but only 50% appeared normal. Probably after a complete nerve section, occurs a reinnervation by inappropriate axons. However abnormal responses seem more due to an immaturity of the transduction mechanism. After the nerve transection the structure of the motor units is modified, this can lead to an increase of the mechanical input to the Golgi tendon organs. A missing of the responses coincides with an alteration of the dynamic sensitivities.

The Sensory Role of the Cruciate Ligaments

Knee joint ligaments have been traditionally considered passive structures only involved in mechanical functions. Evidence proves that they are more than a passive rope-like structure [12]. A variety of studies concerning the presence of mechanoreceptors in cruciate ligaments have been reported [13-16].

Abbot et al., [5] first described the knee ligaments as having rich sensory innervation, than Schultz who described mechanoreceptors in human ACL later in 1984 [17]. Others studies have showed a significant presence of mechanoreceptors in the normal ACL and PCL, playing a key role in proprioception [18-24].

The human cruciate ligaments are characterized by a rich nerve supply and they are innervated by the Posterior Articular Nerve (PAN) of the knee joint, which arise from the posterior tibial nerve usually below the popliteal fossa and other nerve branches arising from obturator nerve, saphenous nerve, common peroneal nerve, quadriceps nerve, sartorious nerve and gastrocnemius nerve.

Three different types of nerve fibres and of nerve endings have been describe in normal ACL:

1) Fibers of large diameter which are fast-conducting mechanoreceptive sensory afferents;

2) Fibers of small diameter slow-conductive nociceptive sensory afferents and

3) Sympathetic efferent vasomotor fibers.

Four nerve endings have been identified in human cruciate ligaments: Ruffini corpuscles, Pacinian corpuscles, Golgi tendon organ like endings and free nerve endings. The mechanoreceptors are mostly placed at the femoral and tibial insertions compared with the midportion of the ACL and PCL and they constitutes about 2.5% of the ligament [6,25,26].

Ligament mechanoreceptors influence movements via the γ-muscle-spindle system [27]. They contribute to the stiffness preprogramming around the joint and are crucial for joint stability maintenance. Therefore the knee ligaments injury would damage the mechanoreceptors and alter neuromuscular functions secondary to diminished somato-sensory informations. Borsa proposed that the functional instability that occurs after ACL injury is a combination of the ligament deficiency and the lack of “coordinated muscle activity” to stabilize the knee joint [28]. A specific reflex arc exists between the ACL and the hamstrings and a contribution of the ACL in the neuromuscular stabilization of the knee [29]. Hamstrings play a crucial role in ensuring knee stability and they directly protect the ACL during movements of the tibia relatively to the femur [30]. However according to Pope et al., [31] this can be not fast enough to prevent injuries. Melnyk et al., [32] studied hamstring activity and the mechanical characteristics of postero–anterior tibial movement secondary to mechanically induced tibial translation in patients with ACL rupture with the aim to investigate whether the subjective feeling of “giving way” is related to any objective difference in hamstring reflexes. They found that ACL rupture causes considerable changes in stretch reflex excitability and they concluded that “giving way” of the knee is not simply related to the decrease in mechanical joint stability, but is closely associated with altered stretch reflex excitability that most probably takes place on the spinal level.

The mechanoreceptors in healthy joints have been widely investigated. More than 1.000 papers matches the words “mechanoreceptor” and “joint” from 1960, but only few reports studied the proprioceptive properties of ACL after injury [33]. For example Denti et al., [21] found normal Ruffini receptors in human ligaments stumps even 3 months after injury. Then the number of receptor gradually decreased and they disappeared at about 1 year after injury. The authors concluded that the residual proprioceptive potential of the ACL stump may decrease with time. According to Sha and Zhao [34] mechanoreceptors in tibial residual of ruptured ACL have a long survival without obvious degeneration and atrophy within 12 months, while other authors reported the presence of mechanoreceptors at 3 years [35] and 4 years after injury [34]. All authors agree that, if the residual ACL fibers are preserved during the ACL reconstruction, the mechanoreceptors existing in the residual stumps may act as a possible source of reinnervation of the graft and they may contribute to restoration of proprioceptive function if well reinnervated [8]. In an animal model Shimitsu et al., [36] showed the regeneration of the mechanoreceptors in the graft after ACL reconstruction using patellar tendon. They did not find any mechanoreceptors at 2 weeks from surgery; however the graft was repopulated by new receptors at 4 weeks after surgery and at 8 weeks. Therefore some authors proposed ACL reconstruction preserving tibial and femoral insertion as much as possible [37,38]. Even if they did not find any significant difference in mechanical stability between patients in whom the stump was preserved and in patients in whom it has been sacrificed, they found significant difference in functional outcome and proprioception. Li et al., [39] stated that remnant preservation in ACL reconstruction can provide better clinical results as compared to remnant sacrificing techniques. On the other hand this procedure is technically demanding and a higher risk of Cyclops syndrome has been reported. More recently two different treatments of partial ACL tear have been compared in an animal model, selective ligament augmentation and ligament reconstruction [40].

Immunofluorescent staining for neurofilament showed an enhancement of proprioceptive recovery in the tendon among the former group if compared to the results observed in the latter one, nevertheless it was inferior to the partial tear group. The authors showed a greater number of cells in the grafted tendons of the animals receiving ACL augmentation surgery and better proprioceptive recovery compared with the reconstruction group. Finally the augmentation group showed higher mechanical strength than either the reconstruction group or the partial tear group. They concluded that selected ACL augmentation promotes tendon graft healing, which appears in further mechanical strength and may represent a potentially desirable surgical alternative to treat partial tear ACL injuries.

Reduction of mechanoreceptors is not only due to a lesion of the soft tissue. Mechanoreceptors are not immutable structures but their properties changes with aging [41]. Aging affects numbers and morphology of mechanoreceptors. This phenomenon could explain why normal aging process is associated with deficits in proprioception.

Conclusion

Mechanoreceptors in normal tissues contribute to stability of the joints. Injuries of ligaments, tendons and muscles contribute to the mechanical instability and to a disturbance in neuromuscular control due to the loss of mechanoreceptors. In our opinion this field remains to be investigated more deeply in the way to clarify the complex relationship between soft tissues and nervous system in normal and pathological conditions. Further studies need to be conducted on mechanoreceptors functions in normal and pathological conditions, in the close future maybe our surgical procedures, rehabilitation protocols for conservative or post-surgical treatments will become modified if proprioception sense will be better addressed.

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