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Wrist proprioception—An update on scientific insights and clinical implications in rehabilitation of the wrist

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ABSTRACT

The field of wrist proprioception, as it relates to rehabilitation and surgery, has gone through a period of intense growth in the past decade. From being primarily focused on the function of the joint and ligaments in patients with wrist trauma or after wrist surgery, the understanding is now that of a greater complexity in treating not just the wrist but the hand and arm as a whole. Proprioception is derived from the Latin words "proprius" – belonging to (oneself) and "-ception" to sense. In other words, how to sense ourselves. To have a complete sense of self, multiple sensory afferents originating from joints, ligaments, muscles, tendons, nerves, skin, vision, and hearing work together to orchestrate a balanced integration of sensorimotor functions, with the true goal to perceive and adapt to the physical world around us. In this update on wrist proprioception, we review current developments in the understanding of proprioception, with an implication for our everyday work as hand therapists and hand surgeons. Each contributing sense—joint, ligaments, muscles, skin, and brain—will be reviewed, and the clinical relevance will be discussed. An updated wrist rehabilitation protocol is proposed where the therapist is guided to rehabilitate a patient after wrist trauma and/or surgery in 4 stages: (1) basic hand and wrist rehabilitation with a focus on reducing edema, pain, and scar formation; (2) proprioception awareness to improve the sense of joint motion and position; (3) conscious neuromuscular rehabilitation where isometric exercises of muscles that are beneficial for a particular injury are promoted, whereas others that are potentially harmful are avoided; and (4) unconscious neuromuscular rehabilitation with training of the reflex and joint protective senses.

Introduction

Proprioception in wrist rehabilitation was the focus of a review paper published in this journal in 2010. The introduction read as follows: "*A PubMed search on the subject of 'proprioception' and 'rehabilitation' will generate close to 2300 related publications. If one adds the term 'wrist', however, the number of articles is dramatically reduced to 20. After eliminating 'stroke' and 'hemiplegia', one is left with only a handful of scientific publications on the subject of wrist proprioceptive rehabilitation, indicating that we are, indeed, at the brink of an entirely new field in hand therapy*."[1]

As we are writing this update on wrist proprioceptive rehabilitation, the same PubMed search was done again (August 2023). A search on "*proprioception*" and "*rehabilitation*" now generates 14,200 publications. The addition of the term "*wrist*" results in almost 200 publications, and eliminating "*stroke*" and "*hemiplegia,*" leaves us with close to 150 publications. The science of wrist proprioception rehabilitation has truly gone through a tremendous expansion in the past 14 years, reflecting the interest in understanding this field and using it to treat our patients.

Proprioception is essentially our "sixth sense," using sensations arising from joints, ligaments, muscles, and skin to provide the brain with information regarding joint position, joint motion (kinesthesia), muscle force, touch, and body control. While the focus of our review is to provide an update on the science of proprioception as it relates to wrist rehabilitation, all these proprioceptive senses need to be taken into consideration—not just the joint itself. Indeed, as Sir Charles Scott Sherrington, who in 1906 first defined proprioception, said: "*This integrative action in virtue of which the nervous system unifies from separate organs an animal possessing solidarity, an individual, is the problem before us.*"[2]

The aim of this review is to give an update on scientific developments in the understanding of proprioception, with an implication for

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our everyday work as hand therapists and hand surgeons. Each contributing sense—joint, ligaments, muscles, skin, and brain—will be reviewed, and the clinical relevance discussed to bring to light, the integrative individual before us.

Joint proprioception

The science of joint innervation

Determining the localization, the receptor type, and the distribution of sensory nerve endings is essential for understanding the proprioceptive properties of different tissue types and the pathophysiological reactions/features of diseases affecting the peripheral nervous system[3] or the hand.[4] This is possible because each receptor type has specific neurophysiological traits and can be determined histologically based on its characteristic morphology. Thus, sensory nerve endings in periarticular tissue, that is, in joint capsules or ligaments, are divided into 4 receptor types according to the classification of Freeman and Wyke,[5] which was modified by Hagert,[6] who added unclassifiable corpuscles as type V.

Histologic methods to depict sensory corpuscles and to study their morphology have improved over the last 10 years with goals of complete visualization and precise analysis of the corpuscular microstructure. Early studies investigated sensory nerve endings using gold chloride,[7] which impregnates not only nerve tissue but also elastic fibers in blood vessels and reticular fibers, thus providing nonspecific imaging of neural elements in tissue.[8–10] This led to the use of specific immunohistochemical markers, which allow a precise differentiation of the sensory nerve endings due to selective delineation of specific neural and perineural structures in sensory nerve endings.[11,12] The main disadvantage of 2-dimensional immunohistochemical investigations is that only a singular staining per slice can be studied. Therefore, the technical limitation of a monostaining analysis led to high amounts of unclassifiable corpuscles.[12,13]

Technical advances in the analysis of sensory nerve endings have been obtained with immunofluorescence staining, enabling simultaneous presentation of different neural and perineural markers, which have resulted in a significant decrease of unclassifiable corpuscles.[14,15]

Further improvements to study the morphology of sensory nerve endings were achieved with 3-dimensional (3D) immunofluorescence analyses by extending the visualization in the z-plane,[16] which provides excellent image quality and allows the study of sensory corpuscles in all 3 dimensions.[17] The inner structures of the corpuscles can be analyzed in detail by placing 2 measurement points. The antibody distribution is displayed as a histogram. After the determination of corpuscle volume, an outer cover displays the shape of the corpuscle (Fig. 1). Furthermore, the precise localization of sensory nerve endings in ligaments has provided the base for the development of 3D ligament models to visualize the distribution of sensory nerve (Fig. 2).[18]

Joint innervation and function

The understanding of functional aspects of sensory nerve endings is another exciting field of interest apart from analyses of their morphologic structure. Mechanotransduction refers to the biological phenomenon wherein mechanical stresses applied to cells are translated into chemical signals that elicit adaptive responses. Mechanotransduction is involved in many critical biological responses from vasodilation to hearing, balance, sensation of joint position, muscle contraction, and touch.[19]

Although the exact mechanisms of mechanotransduction are not completely encoded, past histochemical studies have demonstrated the presence of mechanosensitive epithelial sodium channels in periodontal Ruffini endings[20] as well as calcium-dependent processes.[21] The occurrence and distribution of mechanosensitive ion channels have been studied by analyzing the mechanoproteins PIEZO2 and acid-sensing ion channel 2 in Pacini corpuscles of the human palmar aponeurosis of the hand in healthy controls and patients suffering from Dupuytren's disease.[4] The densities of the free nerve endings and Golgi-like endings corpuscles were slightly increased in patients with palmar fibromatosis. In addition, their Pacini corpuscles were enlarged and displayed an altered shape. Finally, there was also morphologic and immunohistochemical evidence of occasional denervation of the Pacinian corpuscles, although no increase in their number was observed. Interestingly, both PIEZO2 and acid-sensing ion channel 2 were absent from the altered corpuscles. These results indicate that sensory corpuscles within the palmar aponeurosis undergo quantitative and qualitative changes in patients with palmar fibromatosis, which may explain the sensory alterations occasionally reported in patients with Dupuytren's disease.[4]

Findings in healthy and arthritic hand and wrist joints

Carpus

Just to recap, articular branches of the radial, ulnar, median, and musculocutaneous nerve are the main contributors to wrist joint innervation.[22–25] Immunohistochemical investigations of the innervation of carpal ligaments have shown that the pattern varies distinctly, with a pronounced innervation in the dorsal ligaments and in the entire scapholunate ligament, an intermediate innervation in the volar triquetral ligaments, and only limited innervation of the volar radial ligaments.[26] The sensory nerve endings are mainly distributed in the superficial two-thirds of the dorsal radiocarpal ligament and near the bony insertions.[27]

The palmar part of the scapholunate ligament contains a greater number of neural structures than the dorsal or proximal part.[28] Further analyses of the dorsal part of the scapholunate ligament showed that Ruffini endings were significantly more often located at the scaphoid insertion compared to the central or lunate region. In contrast, free nerve endings were significantly more often located in the central parts of the ligaments compared to the scaphoid or lunate region.[18] The transverse carpal ligament, which covers the carpal tunnel, has been investigated in 3 equal parts, namely, the radial, central, and ulnar parts. The density of neural elements was greater in the radial, followed by the ulnar and central part, suggesting that carpal tunnel release in the central region has the least potential of an injury of neural elements and should be taken into consideration when performing carpal tunnel release.[29]

Triangular fibrocartilage complex

The sensory nerve endings of the 7 different structures of the triangular fibrocartilage complex were investigated, including the subsheath of the extensor carpi ulnaris (ECU), the articular disc, the volar and dorsal radioulnar ligaments, the ulnolunate and ulnotriquetral ligaments, and the ulnocarpal meniscoid. Free nerve endings were the predominant receptor type, indicating that nociception has great importance in distal radioulnar joint (DRUJ) proprioception. The articular disc and the ulnolunate ligament are rarely innervated, and both structures have mainly static functions. In contrast, the volar and dorsal radioulnar ligaments are richly innervated, indicating pronounced proprioceptive functions.[12] In fact, patients with detachment of the foveal triangular fibrocartilage complex insertion have been shown to have a decrease in wrist proprioception in 60° and 40° forearm rotation, compared to healthy controls.[30]

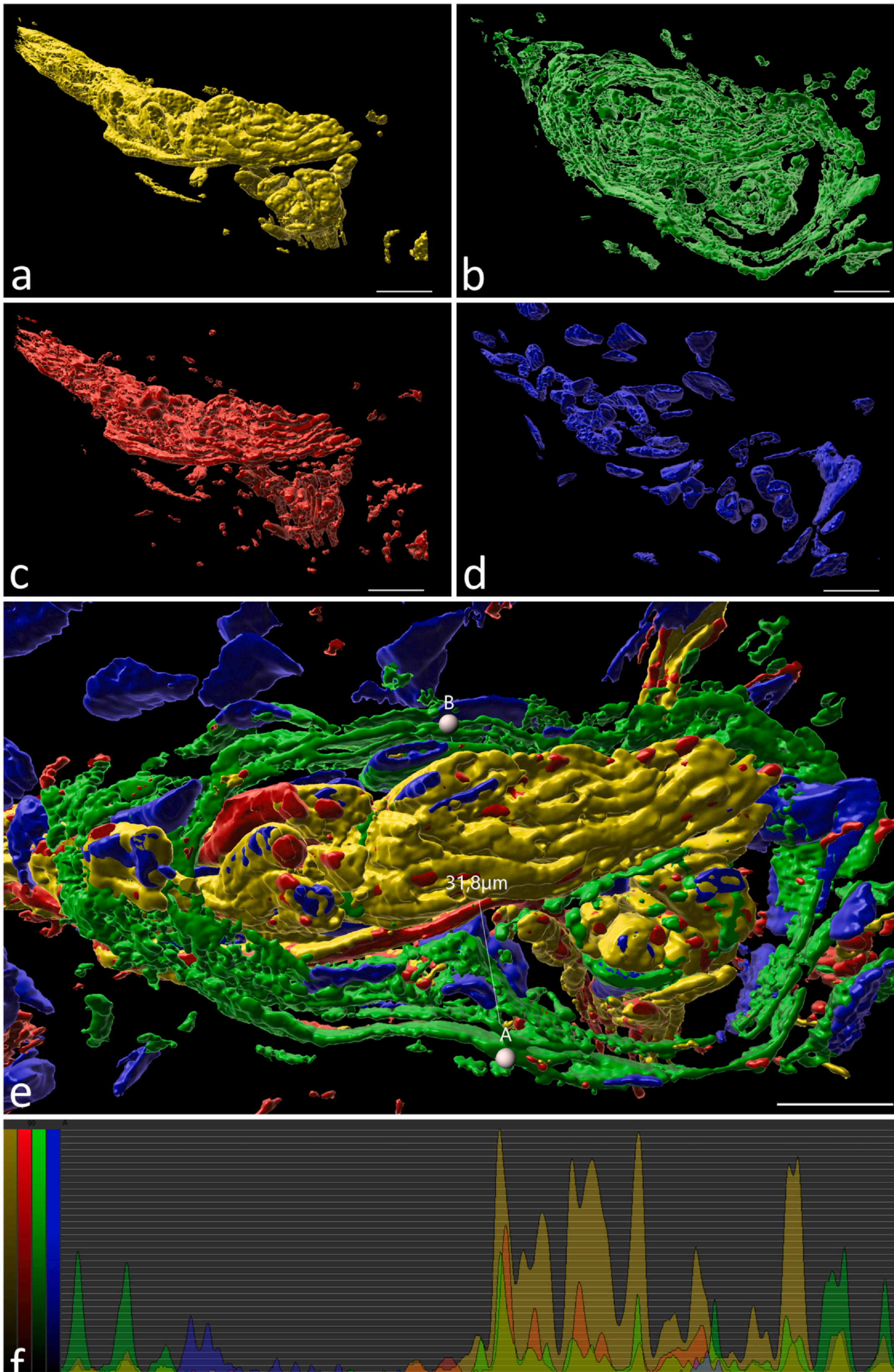

Fig. 1. A 3D model of a Ruffini ending displays the distribution of (**A**) S100, (**B**) p75, (**C**) PGP 9.5, (**D**) DAPI, and (**E**) all immunofluorescent markers simultaneously. The central axon is precisely visualized with S100 and PGP 9.5 (**A** and **C**) and branches out into dendritic terminal nerve endings. The capsule shows strong immunoreactivity for p75 (**B**). Analysis of intrinsic antibody distribution is performed by cropping the 3D model and placing 2 measurement points (**E**). The line connecting both measuring points is displayed as a histogram (**F**), with the voxel intensities displayed on the y-axis and the measurements of length as μm on the x-axis. Original magnification: ×400; scale bar size: 20 μm.

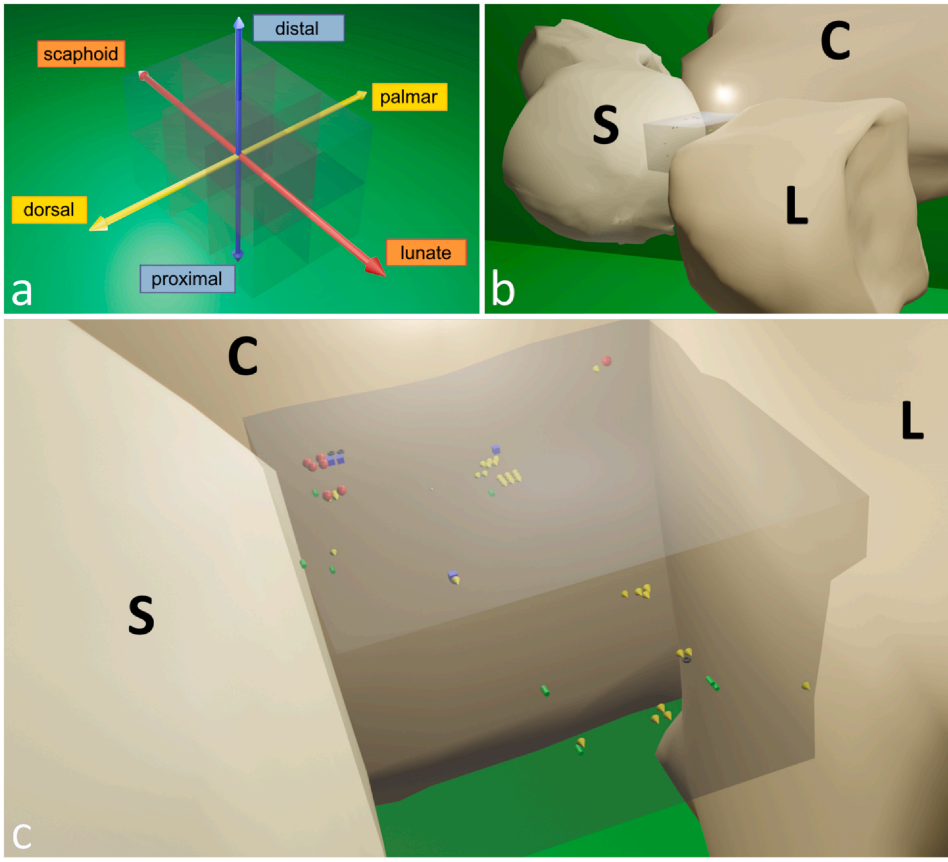

Fig. 2. An illustration of a 3-dimensional ligament model. The dorsal part of a scapholunate ligament is subdivided into 12 anatomic regions along the 3 anatomic axes: proximal-distal, palmar-dorsal, and scaphoid-central-lunate (a). Geometric symbols are assigned to the different types of sensory nerve endings, which are placed into the ligament model. Note the 3-dimensional distribution of sensory nerves within the ligament. Red ball = Ruffini; blue square = Pacini; green cylinder = Golgi-like endings; yellow cone = free nerve ending; black ring = unclassifiable corpuscles; C = capitate; L = lunate; S = scaphoid. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Interosseous membrane of the forearm

An anatomic study of the 6 different structures of the interosseous membrane of the forearm, including the distal oblique bundle (DOB), the distal accessory band, the central band, the proximal accessory band, the dorsal oblique accessory cord, and the proximal oblique cord, showed that free nerve endings were the predominant receptor type in all 6 structures, with the the highest density in the structure closed to the DRUJ (DOB) and proximal radioulnar joint (proximal oblique cord). Furthermore, the DOB had the highest density of Pacini corpuscles, indicating the important proprioceptive control of forearm rotation near the DRUJ, as Pacini corpuscles mediate joint acceleration and deceleration. The lowest amounts of sensory innervation were found in the structures of the central part. Contrary to the carpus, nerve endings were equally distributed throughout the structures, rather than being epifascicular, interstitial, or close to the insertion into bone, which ensures dynamic control in any forearm position. The high density of sensory corpuscles in the structures close to the DRUJ and proximal radioulnar joint indicates their proprioceptive control of the compressive and directional muscular forces acting on these joints.[14]

Basal thumb joint

The innervation of the first carpometacarpal joint (CMC1) arises from the median nerve and its palmar cutaneous branches, the lateral antebrachial cutaneous nerve, and the superficial branch of the radial nerve.[31–33]

While dorsal ligaments, namely, the dorsal radial, the dorsal central, and the posterior oblique ligaments, of the thumb CMC1 joint have an abundance of sensory nerve endings, mainly close to the physical mobile metacarpal region, rather than the rigid trapezial region, the ulnar collateral showed sparse, and the anterior oblique ligament showed no innervation. Ruffini endings were the predominant receptor type, indicating that joint position sense (JPS) is of great importance to the basal thumb joint.[34] In contrast, the innervation pattern of arthritic CMC1 joints is altered compared to healthy ones.[35,36] Where Ruffini endings predominate in CMC1 joints with no to mild osteoarthritis (OA), unclassifiable corpuscles and free nerve endings predominate in patients with pronounced OA.[35]

Clinical relevance

What can we expect to use for proprioception training in an arthritic thumb?

Osteoarthritis is not a disease of joint cartilage. Rather, the cartilage wear seen in OA is regarded as the end stage of a disease that originates in the tissues supporting the joint. Therefore, it has been suggested that the joint should be viewed as a “synovial organ,” where any part of that organ, be it the cartilage, subchondral bone, synovium, ligament, nerve, or periarticular muscle, is involved in the development of joint OA.[37]

The lack of Ruffini endings in CMC1 joint arthritis might be 1 reason for the significant impairment of the active JPS in patients with CMC1 OA compared to healthy subjects.[35,38] However, the influence of age-related decrease of sensory nerve endings remains unclear.[38]

Selective denervation of the CMC1 offers a treatment option in early-stage OA of the CMC1, as it is a simple and minimally invasive surgical procedure with a short postoperative immobilization.[39,40] This may address the polymodal neurogenic inflammation of the articular synovium in arthritic CMC1 joints, as it has been found that the synovium in CMC1 OA display markers of both autonomic, sensory, and glutamatergic nociceptive pathways.[41] An overall improvement in key pinch and grip strength, as well as a reduction in pain scores, have been reported after the procedure.[33,42,43]

Hand therapy to improve the dynamic stability of the CMC1 is applied as a multimodal and staged approach that includes manual release of the adductor pollicis (AP) muscle, joint mobilization to reduce the subluxated metacarpal and realign the CMC1 joint, neuromuscular reeducation and strengthening, use of joint protection techniques, and orthoses as needed with the goal of gradual weaning.[44]

Biomechanical investigations have pointed out that the first dorsal interosseous (IOD1) muscle causes the least dorsoradial translation and highest distal migration of the base of the first metacarpal, whereas abductor pollicis longus (APL) is the primary destabilizer, increasing dorsoradial misalignment.[45] Therefore, the IOD1 should be strengthened with the goal to maintain the metacarpal out of the radially subluxed posture. The neuromuscular reeducation of the IOD1 is initially best performed in the so-called “stable C position” of the thumb, which is achieved through opposing the first metacarpal to the second and third metacarpal resulting in an approximately 30° flexion of the metacarpophalangeal (MCP) joint combined with an opening of the first webspace.

The opponens pollicis is targeted to restore the pronation of the thumb, which is often lost with AP contraction. The abductor pollicis brevis muscle can be selectively trained to open the first webspace. The extensor pollicis brevis is reeducated to break the pattern of the extensor pollicis longus dominance, which reinforces the basal thumb extension. Finally, exercises to strengthen the flexor pollicis brevis muscle are performed with the intent of maintaining the flexion of the MCP joint of the thumb and thus preventing the MCP hyperextension, or zig-zag, collapse. In contrast, strengthening of the extensor pollicis longus and AP muscles should be avoided.[44]

Neuromuscular reflexes

Joint protective reflexes, do they exist?

Neurophysiological studies have demonstrated the importance of joint-protective ligamento-muscular reflexes.[46–50] According to Freeman and Wyke’s theory of an intrinsic reflex arc, a polysynaptic reflex arc originates from ligamentous and capsular sensory nerve endings. This influences the activity of the joint-stabilizing musculature via gamma-motoneurons and thus coordinates muscle tone to maintain joint stability during rest and movement.[51,52] Excitatory and inhibitory reflex arcs that elicit from the ligamentous receptors modulate the activity of the joint-stabilizing muscles. This subtle interaction between ligaments and muscles protects the joint from overload and potential injury.[53] Thus, the ligamento-muscular reflexes provoke a muscular contraction of the protective muscles or a muscular activity inhibition of the destabilizing muscles in each wrist position.

It has been found that electrical stimulation of the dorsal part of the scapholunate ligament[54] or the dorsoradial ligament of the CMC-I joint[49] elicits immediate, polysynaptic reflexes that serve as joint-protective reflexes. These reflexes of the scapholunate ligament were eliminated in healthy controls after desensitization of the posterior interosseous nerve.[55] The same results were obtained after anesthesia of the skin and periarticular tissue of the CMC1 joint.[56]

The denervation of the wrist is a palliative procedure indicated to reduce the level of chronic pain in irreversible wrist pathologies with well-preserved joint mobility. It involves the desensitization of articular branches innervating the wrist, which have no impact on the sensibility of the skin or motor functions of the wrist.[57] The complete wrist denervation procedure according to Albrecht Wilhelm involves the surgical denervation of 10 afferent articular nerve branches.[57]

A clinical study investigating patients after complete wrist denervation compared to healthy controls observed no significant alteration for JPS, wrist reflex time, and force after wrist denervation.[58] These results are in line with another study, which has not found significant differences in JPS following posterior interosseous sensory neurectomy of the wrist.[59] The results of both mentioned studies are controversial to the studies of the ligamento-muscular reflexes. This is explained by the fact that afferents sampled from the median and ulnar nerves at the wrist were classified as joint afferents in 15%. However, the majority of wrist proprioceptive afferents are of cutaneous origin (72.5%), with 12.5% derived from muscle spindles and tendon organs.[60] This explains why no significant differences in wrist reflex time (stretch reflex) were observed after wrist denervation, as muscle spindle afferents and cutaneous receptors are contributing to this reflex sense, and both are unaffected by wrist denervation. In contrast, afferent sensory nerve endings in ligaments are stimulated directly. Therefore, articular reflexes are lost after denervation. The muscle stretch reflex represents proprioception as a complex interplay of afferents from the joint, the muscles, the periarticular tissue, the skin, and the central nervous system, which partially compensate for each other through their diverse input. In conclusion, denervation is pain relieving in patients with severe joint degeneration and pain. However, it is of paramount to exercise caution with a healthy nerve capable of providing reinnervation and proprioception to preserve wrist proprioception, as demonstrated by ligamento-muscular and joint-protective reflexes.

Clinical relevance

The forearm muscles contribute to the carpal alignment under physiological conditions as follows: the extensor carpi radialis longus (ECRL) and extensor carpi radialis brevis (ECRB), the APL, and the flexor carpi ulnaris (FCU) are carpal supinators. In contrast, the ECU induces a pronation of the carpus.[61,62] The flexor carpi radialis (FCR) muscle provides dual wrist stability, promoting both supination and pronation of the scaphoid and triquetrum, respectively.[61,62] These muscles work synergistically in healthy wrist joints and are targeted for neuromuscular retraining exercise strategies in patients with specific wrist ligamentous injuries.[63]

Patients with partial or incomplete scapholunate ligament injury (without static dissociation) require dynamic stabilization exercises of the carpal supinator muscles, including the ECRL, ECRB, APL, and FCU. Isometric strengthening of the ECRL/ECRB and FCU should ideally be performed in forearm pronation, which weakens the force of the ECU as a counterpart, while the APL should be strengthened in a neutral forearm position[61,62] (Fig. 3A).

The promotion of triquetral pronation is the goal of dynamic stabilization exercises performed in lunotriquetral instability. Muscles that act as carpal supinators, such as the ECRL, ECRB, APL, and FCU, should not be trained. Therefore, the treatment is focused on ECU exercises in the early stages and combined ECU and FCR muscle activation (reverse-dart thrower motion) in later rehabilitation stages[61,64] (Fig. 3B).

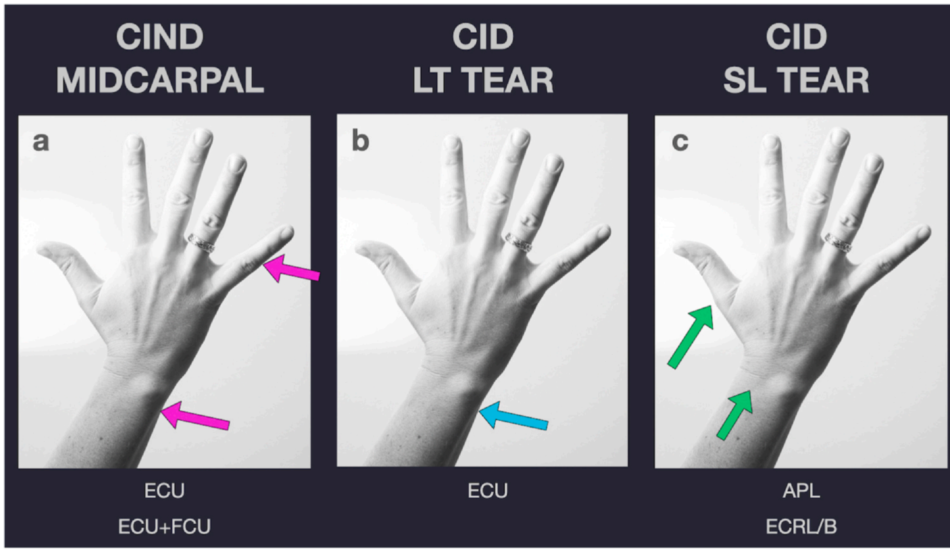

Fig. 3. Examples of conscious neuromuscular training for nonoperative treatment in patients with (**A**) palmar midcarpal instability = exercise the ECU and perform co-contractions of the ECU/FCU through little finger isometric abduction; (**B**) In partial lunotriquetral tears, ECU should also be exercised in forearm neutral; (**C**) in partial scapholunate tears, APL exercises in forearm neutral and ECRB/ECRL in forearm pronation are ideal. CIND = carpal instability nondissociative; CID = carpal instability dissociative; LT = lunotriquetral; SL = scapholunate; ECU = extensor carpi ulnaris; FCU = flexor carpi ulnaris; APL = abductor pollicis longus; ECRB = extensor carpi radialis brevis; ECRL = extensor carpi radialis longus.

Palmar midcarpal instability, defined as a carpal instability nondissociative between the proximal and distal carpal rows, requires dynamic stabilization exercises of the ECU in neutral forearm position and co-contractions of the ECU and FCU, which can be done through isometric activation of little finger abduction (Fig. 3C).[61,62] Dynamic stabilization of the DRUJ is achieved by the pronator quadratus (PQ) and the ECU. Joint congruency is particularly an important function of the PQ.[61,62]

The role of the skin

The skin is by far the largest organ of the human body, constituting as much as 16% of our body weight. In general, our skin contains approximately 300 million cells, and 1 inch of skin is predicted to have about 1000 nerve endings. Although the skin is well known to have an important role in mechanoprotection and mechanosensation through mechanoreceptors in the epidermis, dermis, and subcutaneous fat, the role of skin in proprioception and joint control has been underappreciated until recently.

The importance of skin in proprioception was highlighted when the 2021 Noble Prize in Physiology or Medicine was awarded to Drs Julius and Patapoutian for their groundbreaking work in "*understand [ing] how heat, cold, and mechanical force can initiate the nerve impulses that allow us to perceive and adapt to the world around us.*"[65] The core of their findings is in relation to 2 receptors in the skin, the TRPV1 and PIEZO2 receptors, which are essential in an individual's interaction with the physical world as they regulate the experience of touch and proprioception.

In addition to the 2 receptors above, the skin, just as the joint, contains 5 subtypes of mechanoreceptors. The Ruffini ending, Pacini corpuscle, and free nerve endings are similar in type and function to those found in ligaments. In addition, 2 other mechanoreceptor types are found in the dermal-epidermal layer: the Meissner corpuscle and the Merkel disc receptor[66] (Fig. 4). The Ruffini and Merkel receptors are both slowly-adapting mechanoreceptor types, located in the deep and superficial layers, respectively. In the hand, the Ruffini endings are primarily found close to the nail bed, signaling dynamic and static skin indentations over time, while the Merkel cells are in the epidermal sweat ridges of the palm and tips of the fingers, signaling static skin pressure.[67] Contrarily, the Pacini and Meissner corpuscles are both rapidly adapting in the deep and superficial skin layers, respectively. Both receptors are adaptive to load and vibrations, with sensitivities to frequencies between primarily 30-500 Hz (Ruffini) and 5-50 Hz (Meissner).[68]

The distribution of mechanoreceptors varies in the body. In general, a youth will have up to 270,000 mechanoreceptors in the skin, with about 15% located in the palms of the hands.[69] Of these, the vast majority are found in the fingertips. A recent publication on the distribution of Pacini corpuscles in the tips of fingers has shown that these mechanoreceptors are primarily found on the radial side of digits II-V while evenly distributed in the entire tip of the thumb. As the Pacini corpuscle in the skin is specialized in sensing friction and very detailed features, this anatomic location indicates its importance in pinch and tactile discrimination.[70]

It is also important to remember the supreme innervation of the skin by sensory nerve branches. Cutaneous branches from the radial, median, and ulnar nerves are superficially located in the hand and wrist, rendering them susceptible to injury or adhesions following trauma or surgery. Pain has been found to be one of the most important factors in affecting proprioception following distal radius fractures,[71] and persistent pain after wrist trauma should alert the clinician to the possible involvement of superficial sensory nerve branches.

Clinical relevance

The innervation of the skin can be affected by diseases, age, and trauma. Past histologic studies have demonstrated denervation of cutaneous sensory corpuscles in diabetic neuropathy in humans,[72] structural and immunohistochemical alterations in periarticular Pacini corpuscles in rats and cats after peripheral nerve injury,[73] as well as a reduced density of Meissner corpuscles in Charcot-Marie-Tooth disease.[74]

Recently, declining levels of brain-derived neurotrophic factor and tropomyosin receptor kinase B, both members of the neurotrophin family that also interact with p75 and important for mechanotransduction, have been reported in aging cutaneous sensory nerve endings,[75] as well as a denervation of Meissner corpuscles

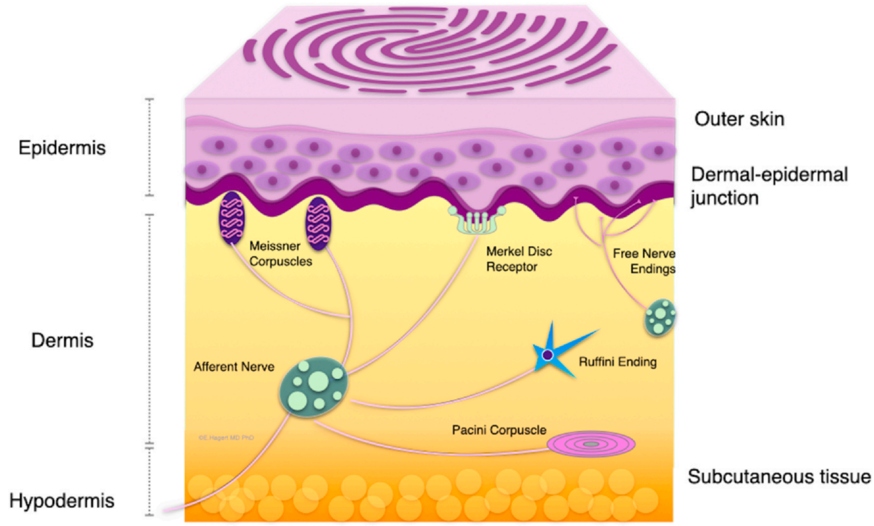

Fig. 4. Illustration of the innervation of skin. Mechanoreceptors of Merkel disc receptor and Meissner corpuscle types are found in the dermal-epidermal and superficial layers of the skin. Pacini corpuscles and Ruffini endings are found In the deeper and subcutaneous layers. Free nerve endings are distributed through both superficial and deep layers.

affecting tactile spatial sensitivity. Furthermore, the total number of mechanoreceptors in the skin is known to decrease by 8% per decade,[69] meaning that the senescent (60+) hand and wrist will have 4-6 times fewer skin receptors than younger counterparts, likely contributing to the loss of sensorimotor function seen in elderly.[75]

In rehabilitation of a traumatized or surgically treated hand/wrist, it is of utmost importance to dedicate time to treating skin and scars. Adhesions between skin and underlying tendons will affect motion and should the scar additionally engage sensory nerve branches, the result may be painful paresthesias associated with movement. Recently, a new rehabilitation concept in hand therapy has been proposed called "think in nerve length and layers," which serves to address joint motion, neural tension, and superficial nerves through motion, kinesiotaping, and isometric exercises.[76] The role of skin, sensory nerves, and motion is illustrated in a patient case (Video 1).

Supplementary material related to this article can be found online at doi:10.1016/j.jht.2023.09.010.

Brain interaction

The rapidly advancing technology involving prosthetic limbs, brain-body interfaces, and artificial intelligence has driven a large scientific movement to understand the interaction between the brain and the body regarding joint and movement control, spatial orientation, and the role of various senses in our interaction with the physical world. Due to the immensity of the subject, we will but briefly review the relevance of brain interaction, including audiovisual senses, in the control of the hand and wrist.

The ability to use functional neuroimaging to assess the role of peripheral sensory inputs and brain interaction has given us an added complexity and dimension to understanding proprioception. In a recent publication investigating the role of vision and proprioceptive feedback (muscles, joints) in wrist stabilization using functional magnetic resonance imaging (fMRI), it is found that the action needed guides the senses used.[77] For example, in actions where controlled stability and precise motion are required, as in holding a glass full of water, conscious visual acuity is primary. Contrarily, in actions with unpredictable external events, that is, reflex control while playing a sport or driving a car, vision plays a secondary role to the unconscious proprioceptive feedback from the wrist through muscles, joints, and skin.

The ability to use fMRI to understand the integrative action on a spinal cord level has also emerged in recent years.[78] Spinal cord investigations have previously been limited to electrophysiological techniques, which have inherent shortcomings. Spinal fMRI has been able to provide in vivo and 3D neural maps, where sensory input from skin and muscle afferents in the same aspect of the hand and arm are confirmed to enter the same segments in the spine, and the sensorimotor action is detected on a cervical spinal level regardless of the type of peripheral stimuli used (ie, light touch, passive motion, vibration) likely due to the collective input from mechanoreceptors in skin, muscles, and joints.[79]

The effect of aging on the brain and proprioception is also the subject of ongoing and recent investigations. fMRI comparing sensorimotor input to detect hand motions (kinesthesia) in young and elderly subjects has revealed that the afferent stimulus from touch is better preserved than the proprioceptive input from muscles and joints.[80] Additionally, multisensory modalities are found to enhance proprioception in the elderly if the sensory input is not perceived as distracting, for instance, as in audiovisual cues.[81,82]

Clinical relevance

Multisensory modalities are thus superior in proprioception training, as shown in studies on the knee joint where enhanced kinesthesia and conscious proprioception control are seen when combining mirror training with mechanical vibration stimulation of the hamstrings,[83] and improved muscle control is achieved when combining knee extension exercises with auditory feedback from electromyography signals in the quadriceps muscles.[84]

Even in mirror training, which has traditionally been thought to be a purely visual modality in improving unilateral hand function by observing the mirror reflection of the healthy, contralateral hand, recent research has shown that the actual effect of mirror training is founded on both visual and proprioception (muscle) feedback from both arms, and not just visual in origin.[85]

Proprioception in wrist rehabilitation

Our review of updates in the science and clinical implications of proprioception makes it evident that we are dealing with a huge,

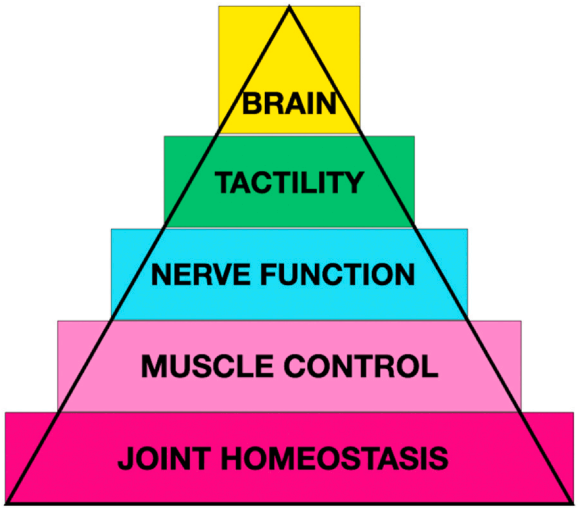

Fig. 5. The Hagert Maslow Pyramid of joint proprioception. For a normal wrist function, the foundation is a joint that is stable and pain free, with balanced muscle control through normal nerve function in the upper limb, maintained skin sensation and integrity, and integrated conscious and unconscious proprioception through vision, hearing, and central nervous system integration.

challenging, and inspirational field, which at times can be overwhelming in our daily treatments of patients.

In this final section of our manuscript, we wish to conclude with a practical approach to dealing with our patients in need of wrist proprioception rehabilitation.

As written above, "*the actions needed guide the senses used*." In other words, to think that rehabilitation of an injured wrist is to focus solely on the joint itself is to underappreciate the complexity of proprioception rehabilitation.

Rather, the needs of wrist proprioception rehabilitation should be seen as a Maslow pyramid of hierarchies (Fig. 5). For a normal wrist function, the foundation is a joint that is stable and pain free, with balanced muscle control through normal nerve function in the upper limb, maintained skin sensation and integrity, and integrated conscious and unconscious proprioception through vision, hearing, and central nervous system integration.

Hagert wrist proprioception protocol

A first protocol for structured wrist proprioception rehabilitation was proposed in the original review from 2010,[1] and as part of our update on the subject, an updated and simplified protocol is seen in Table 1. We will briefly review each stage which aspects of proprioception senses are involved and how these can be implemented in hand therapy practice.

Stage 1: basic hand and wrist rehabilitation

Immediately following a hand or wrist trauma or surgery, the first stage is that of simply providing pain relief, control of edema, and management of possible scars.

Therapy at this stage may include:

- Elevation exercises and gentle range of motion (ROM), as permitted.
- Use of compression to reduce edema (ie, Coban, compression gloves).
- Scar management through massage and, if available, with the aid of LPG (lipo-mechano-massage), ultrasound (video 2).
- Think in nerve length and layers (video 1).
- Paraffin baths to soften skin and joints.
- Possible use of tuning fork therapy to stimulate scar and edema management, as well as stimulate sensory nerve endings in the skin (Pacini, Meissner mechanoreceptors).

Supplementary material related to this article can be found online at doi:10.1016/j.jht.2023.09.010.

Stage 2: proprioception awareness

Once the most acute phase after trauma or surgery has passed, and pain and edema are under control, the next phase is to stimulate proprioception awareness, as pain and periods of immobilization often lead to a sense of "disconnection." Stimulation of skin (tactility) and the use of visual input are keys in this stage.

Modalities that can be used to enhance proprioception awareness include:

- Mirror therapy.
- Kinesiotaping—both for improved proprioception awareness but also to promote skin and joint motion.
- Training of JPS through nonblinded and blinded tests of JPS, as measured with a goniometer.
- Vibration therapy, as in tuning forks over muscle-tendon units to stimulate the sense of joint motion (kinesthesia; Video 3).

Supplementary material related to this article can be found online at doi:10.1016/j.jht.2023.09.010.

Stage 3: conscious neuromuscular control

The principle of the third stage, conscious neuromuscular control, is to actively work with rehabilitation of muscles that are beneficial to the recovery following a specific wrist injury/surgery while avoiding muscles that may be harmful. For details, see the section on neuromuscular control above.

Table 1
Hagert proprioception rehabilitation protocol

Stages	Concept	Principles	Therapy modalities	Senses
1	Basic hand and arm rehabilitation	Pain edema scar	Compression Massage Paraffin baths TINLL Early ROM	Brain Skin Nerve
2	Conscious proprioception awareness	Proprioception awareness Kinesthesia joint position sense	Mirror therapy Kinesthetic taping JPS training	Brain Skin Nerve Muscle
3	Conscious neuromuscular control	Conscious-specific muscle training	Isometric Eccentric Co-activation	Brain Skin Muscle
4	Unconscious neuromuscular training	Reflex neuromuscular training	Slosh-pipe Balance plate Power ball®	Brain Muscle Ligament

ROM = range of motion; JPS = joint position sense; TINLL = think in nerve lengths and layers.
Guidelines for staged rehabilitation of the hand and wrist.

Brief examples of active neuromuscular training programs include (Fig. 3):

- SL partial tears (nonoperative treatment): isometric exercises of the ECRL/B with the forearm in pronation and the APL in neutral forearm position
- LT partial tears (nonoperative treatment): isometric strengthening of the ECU, with the forearm in neutral
- DRUJ instability: isometric strengthening of the PQ and ECU

Stage 4: unconscious neuromuscular control

The final stage of wrist proprioception rehabilitation is that of unconscious, or reflex, muscle control. As this stage aims to induce joint perturbations and train for uncontrolled situations, this stage of training should be done when the patient has regained good, conscious motor control of the wrist. As mentioned above, basic science studies have shown that reflex joint control is primarily done through joint and muscular proprioceptive input, rather than visual cues, so training in this stage should be done both with visual and without visual input.

Techniques to train unconscious neuromuscular control include:

- Slosh-pipe exercises.
- Use of a Powerball, TrueBalance, or similar device (see video 4).
- Balancing a ball on the floor or against a wall.

Supplementary material related to this article can be found online at doi:10.1016/j.jht.2023.09.010.

Conclusion

As we begun with a quote by Sir Charles Scott Sherringon, we will conclude with another: "Essential to a great discoverer, in any field of Nature, would seem an intuitive flair for raising the right question. To ask something which the time is not ripe to answer is of small avail. There must be the means for reply and enough collateral knowledge to make the answer worth while."[2] The field of proprioception has reached a stage where we have an abundance of collateral knowledge. We may thus conclude as follows: proprioception is a multisensory modality with receptors in skin, muscles, and joints contributing information to the spinal cord and central nervous system for integrative conscious and unconscious control of our body in relation to the physical world around us. All senses are important and need to be considered when rehabilitating a patient following a hand or wrist injury or surgery. A 4-stage wrist proprioception rehabilitation protocol is recommended to guide a patient to a restored wrist function: (1) basic rehabilitation principles for pain and edema management; (2) reconnection of the traumatized wrist through conscious proprioception awareness; (3) specific neuromuscular rehabilitation exercises to promote muscle function; and (4) unconscious reflex neuromotor control of the joint.

Declaration of competing interest

The authors declare that they have no conflicts of interest and no relevant financial disclosures. The authors received no funding for the manuscript.

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