Proprioception of the Wrist Joint: A Review of Current Concepts and Possible Implications on the Rehabilitation of the Wrist

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ABSTRACT:

Study Design: Narrative review. Recent years have brought new research findings on the subject of wrist joint proprioception, which entails an understanding of the wrist as part of a sensorimotor system where afferent information from nerve endings in the wrist joint affects the neuromuscular control of the joint. Understanding of proprioception is also essential to adequately rehabilitate patients after wrist injuries. The aim of this narrative review was to give the reader a background of proprioception as it relates to neuromuscular control and joint stability, what is presently known in relation to the wrist joint and how these findings may be applied to the field of wrist rehabilitation.

Level of Evidence: 5.

A PubMed search on the subject of "proprioception" and "rehabilitation" will generate close to 2,300 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.

The term "proprioception" is derived from the Latin "proprius"—belonging to one’s own, and "-ception"—to perceive, that is, the ability to sense and perceive one self. This term has been used since the early 20th century to indicate the sensory perception and subsequent motor control of posture, balance, audiovisual-motor coordination, and joint stability. In the century that has passed since its introduction into the scientific community, the term has been exploited to entail any and all of these various sensory modalities. In 1997, in an attempt to illuminate the part of proprioception research dealing with only joint control, experts in the field of proprioception and neuromuscular joint stability coined the phrase "sensorimotor function." This term has since been synonymous with the "total integration of sensory, motor, and central processes pertaining to joint stability." Hence, joint sensorimotor functions entail both conscious and unconscious sensations, and thus both measurable and immeasurable qualities. For the sake of clarity, the word "proprioception" will henceforth only pertain to the subject of sensorimotor function.

The aim of this narrative review is to give the reader an introduction to the research field of proprioception, as it relates to sensorimotor function and neuromuscular joint control, an assessment of what is currently known in relation to the wrist joint, and how this knowledge, in conjunction with what is known from other joints, may be applicable to the field of wrist rehabilitation. As proprioception research entails use of complex and somewhat confusing terminology, a glossary of pertinent terms is presented at the end of the manuscript to assist the readers of this review.

THE BASIS OF PROPRIOCEPTION: INTRODUCTION

In order for a joint to have a proprioceptive function, certain anatomical and physiological criteria must be met (Figure 1). In short, sensory end organs reactive to joint pressure, motion, and velocity (so-called mechanoreceptors) need to be present in joint ligaments and/or joint capsule. When stimulated, these...
mechanoreceptors are believed to signal afferent information that is transmitted to the dorsal horn of the spinal cord, where the information takes one of two paths. The immediate path is a monosynaptic relay of information from the dorsal to the anterior horn, which serves to provide fast control of muscles around the joint. The secondary pathway is a local and/or segmental polysynaptic interaction, where afferent information is transmitted along the dorsolateral and spinocerebellar tracts of the spinal cord to supraspinal targets. Some information is transmitted to the cerebellum, which is the primary localization for the complex integration of somatosensation and proprioception, and concerns the unconscious neuromuscular control of a joint. Furthermore, information is passed to the pre-/primary motor- and sensory cortices, where the conscious appreciation of joint motion is generated.

The specific functions of mechanoreceptors, types of proprioceptive reflexes, and the sensorimotor modalities of joint control will now be discussed in more detail and related to what is known from studies on the wrist joint.

Joint Mechano-receptors—Types and Functions

Ruffini Ending

The Ruffini ending was first described by Italian histologist Angelo Ruffini in the 19th century. Synonyms for this ending are dendritic or spray ending (Table 1). Microneurographic recordings from Ruffini endings in cat knee intra-capsular ligaments have revealed that this is a slowly adapting, low-threshold receptor, which is constantly reactive during joint motion. Additionally, these endings have been found to react to axial loading and tensile strain in the ligament, but not to perpendicular compressive joint forces, revealing their importance in signaling joint position and rotation, rather than direct pressure. These characteristics are believed to be of importance in the regulation of stiffness and preparatory control of the muscles around the joint.

The Ruffini ending is the predominant mechanoreceptor type found in wrist ligaments, indicating a primary importance of wrist sensorimotor function in monitoring wrist positions and motions.

Pacini Corpuscle

The Pacini corpuscle is named after 19th century Italian anatomist Filippo Pacini. Although the eponym is primarily used for this receptor, it is at times referred to as a lamellated sensory corpuscle, indicating the thick, layered capsule that characterizes this nerve ending. The Pacini corpuscle differs from the Ruffini ending, in that it is a rapidly adapting, high-threshold receptor sensitive to joint acceleration/deceleration that is able to sense mechanical disturbances occurring even at a distance. Contrary to
the Ruffini ending, it is sensitive to compressive but not tensile forces. These characteristics make the Pacini corpuscle ideal for sensing sudden joint perturbations, and signal during possibly noxious joint motions. Thus, it appears logical that the Pacini corpuscle is the most abundant receptor found in the lateral ankle ligaments, where its function is ideal for rapid signaling of potentially damaging joint perturbations in a ligament system frequently subjected to distortion and injury. In the wrist, however, the Pacini corpuscle has only been identified occasionally, suggesting that these functions are of minor importance in wrist neuromuscular stability.

Golgi-like Receptor

This nerve ending was named after anatomist Camillo Golgi, who originally discovered and defined this sensory end organ as the “Golgi tendon organ” found in myotendinous junctions. The nerve ending found in ligaments is a type of spray ending, belonging to the same family as the Ruffini ending, and they have even been suggested to be variations of the same receptor. The Golgi-like ending is, therefore, silent in the immobile joint and only active at the extremes of joint motion.

The Golgi-like ending has, so far, only been identified in the large dorsal wrist ligaments, the dorsal radiocarpal (DRC) and dorsal intercarpal (DIC) ligaments, which traverse both the radiocarpal and midcarpal joints. Although the DRC is considered important in stabilizing the wrist in flexion and pronation, the DIC is attributed importance in maintaining transverse stability of the proximal carpal row, as well as indirect stability of the dorsal midcarpal joint space. The finding of Golgi-type endings in these ligaments appears rational, as this receptor is important in monitoring tensile strain in the ligament during ultimate angles of joint motion.

Innervation Distribution in the Wrist

The existence of mechanoreceptors in wrist ligaments was first reported by Petrie et al. in 1997. Using a gold-chloride staining technique and light microscopy, mechanoreceptive nerve endings were identified in three volar wrist ligaments. The distribution of these nerve endings was variable, with mechanoreceptors present in about 1/3 – 1/4 of the ligaments analyzed. In the past five years, the mechanoreceptive properties of wrist ligaments have been studied using more advanced immunohistochemical techniques, light microscopy, and/or laser confocal microscopy and digital imaging. These studies on the innervation of wrist ligaments have revealed variations in the distribution of mechanoreceptors and nerve endings both within the ligament and within the joint. Nerve endings are predominately found close to the
lignament insertions into bone, where the higher stiffness in collagen fibers within the ligament ensures a firing of the receptors only at the extremes of joint angles.\(^{25}\) In the longer wrist ligaments, especially the DRC and DIC ligaments, mechanoreceptors are also found in the pliant epifascicular regions, where they are more readily stimulated and thus able to signal throughout the range of wrist motions.\(^{8,24}\)

The innervation is, furthermore, most pronounced in the dorsal and triquetral wrist ligaments—the DRC, DIC, dorsal scapholunate (SL) palmar lunotriquetral, and triquetrocapitate/hamate ligaments.\(^{9}\) The radial and volar wrist ligaments, on the other hand, consist of densely packed collagen fibers with little to no innervation (Figure 2). This arrangement is interesting, as it entails a differential function of the wrist ligaments in maintaining stability. The ligaments of the radial column of the wrist are dense structures, designed to withstand the axial loads transmitted through this part of the wrist. The dorsal and triquetral ligaments, however, are sensory important structures, which, since they traverse both the radiocarpal and midcarpal joints, signal throughout joint motion.

This anatomical and physiological arrangement of the wrist ligaments was recently illuminated by the IFSSH committee on the biomechanics of the dart-throwing motion (DTM) of the wrist.\(^{26}\) In their report, the ligaments stabilizing the distal pole of the scaphoid, namely the scaphotrapeziotrapezoid (STT) and scaphocapitate (SC) ligaments are regarded as mechanically important in constraining and guiding the DTM. Contrarily, the ultimate stops of DTM, the richly innervated DIC and the volar triquetro-capito-hamate ligaments (TqCH), are proposed to be important in a sensory feedback to the muscles active in the DTM—primarily the flexor carpi ulnaris (FCU) and extensor carpi radialis brevis/longus (ECRB/L).\(^{26,27}\)

**Proprioceptive Reflexes and Pathways**

In 1958, Palmer was the first to demonstrate the existence of reflexes between ligaments in a joint and the muscles acting on that joint.\(^{28}\) In his study, the effect of direct tension on the medial collateral ligament of the knee resulted in fast reflex response in periarticular muscles, which he interpreted as joint protective reflexes. Since then, similar studies on joint ligamento-muscular reflexes in humans have been documented in the knee, ankle, shoulder, elbow, and recently, wrist joint.\(^{27,29–32}\)

As mentioned above, the reflexes elicited from ligaments are transmitted to the dorsal horn of the spinal cord for local (spinal) mono- or polysynaptic reactions or supraspinal transmission of information. The spinal and supraspinal reflexes are highly complex reactions that serve to adequately control the wrist joint. Although these reactions may seem remote from daily hand therapy practice, an elemental knowledge of these is needed to understand later
discussions on rehabilitation. In a review paper published by Bawa et al. in 2000,33 the complex control of the wrist joint is exquisitely delineated. What shall follow below is but a condensed overview of spinal and supraspinal reactions.

**Spinal Reflexes**

**Monosynaptic Reflex**

The fastest and simplest spinal reflex is the monosynaptic reflex, also called the H-reflex, where information from the periphery (skin, joints, tendons) is transmitted through the dorsal horn and directly relayed to the anterior horn for immediate muscle control. The most commonly known H-reflex is the patellar tendon reflex, where a tendon tap on the patellar tendon of a flexed knee will result in an immediate contraction of the quadriceps muscle and extension of the knee joint.

The H-reflex is frequently thought to be involved in joint protective reflexes.25,34 However, controversy exists regarding protective reflexes, since the efficacy of a defensive reflex is entirely dependent on the immediacy of the ligamento-muscular reaction, hence the afferent-efferent transmission of information must be fast enough to break a potentially damaging joint motion.

Experiments on the excitation of human flexor motoneurons have shown that stimulation of the median and/or ulnar nerves at the level of the wrist joint elicit monosynaptic excitations of the flexor carpi radialis and ulnaris (FCR/FCU), occurring within 20 milliseconds after stimulation.35 The ulnar nerve, in particular, was believed to be important in contributing proprioceptive feedback to spinal motoneurons.36 Hence, nerves transmitting information from the human wrist joint have the physiological properties necessary to elicit immediate joint protective reflexes.

**Polysynaptic Reflexes**

The polysynaptic reflexes are transmitted through two or more interneurons, before resulting in an efferent, muscular reaction. These reflexes can at any time be influenced both by local interactions from Renshaw cells and/or homonymous/heteronymous interneuron connections, as well as descending supraspinal control.33 When speaking of polysynaptic reactions, certain terminology should be explained:

*Feed-forward inhibition* is defined as the modulation of a reflex from descending (cortical) control and is believed to be important in controlling the specificity of arm and hand movements.37

*Feedback inhibition* is the modulation of reflexes from peripheral input, that is, modulation of ongoing wrist extension as muscle spindles in wrist flexors react to stretch. This is primarily thought to be of importance in the control of velocity, onset, and termination of motions.38

*Reciprocal inhibition* is mediated through the so-called Ia or Ib inhibitory interneurons, which mediate inhibition to antagonist muscles during voluntary movement,39,40 that is, inhibition of the wrist extensor muscles during voluntary wrist flexion.

*Recruitment inhibition* is primarily mediated through Renshaw cells, which are specialized interneurons acting to control repeated firing of motoneurons. This action results in inhibition of synergistic motoneurons but generally not in antagonistic muscles, that is inhibition of flexor motoneurons after prolonged wrist flexion.41

Hence, reflexes occur at the spinal level to control muscle activity of both agonist and antagonist muscles (recurrent and reciprocal inhibition, respectively). These interactions are influenced by both central and peripheral stimuli (feed-forward and feedback inhibitions), which in the latter instance originate from receptors in the skin, tendons, and ligaments. The polysynaptic reflexes and interactions described above are generally predictable in the muscle control of the lower extremities of cats, monkeys, and humans.41 However, in the muscle control of the upper extremity, in particular that of the forearm and hand, the arrangement is far more complex.

At the spinal level, Ia and Ib inhibitory interneurons are known to contribute to short-latency (mono-/disynaptic) reflex control of the forearm muscles acting on the wrist.40 For instance, excitation of Ia and Ib inhibitory interneurons (which inhibit antagonist muscles) elicit reflexes from the ECR to the FCR during voluntary wrist extension. However, this inhibitory pattern does not only move from the ECR to the FCR, but in the human act in a bidirectional manner (so-called heteronymous connection).33,42 Hence, during voluntary wrist flexion this ECR to FCR activity is decreased, whereas the inhibition is completely abolished during co-activation of agonist and antagonist muscles. The ECR and FCR interneurons can additionally inhibit one another simultaneously, which is thought to be of importance during wrist ulnar deviation where the extensor carpi ulnaris (ECU) is the primary motor. That all of these actions occur in voluntary wrist motion suggests a descending control of the inhibitory interneurons,33 which allows a precise adaptation of wrist stability for specific tasks.43

The Renshaw cells generally counteract the action of the Ia and Ib inhibitory interneurons. As mentioned above, these act only to inhibit synergistic, but not antagonistic, muscles. This holds true for all the other joints but the wrist,33 where the Renshaw cells additionally inhibit antagonist muscles. Hence, the ECR and FCR receive bidirectional Renshaw cell inhibitions, which allows the ECR/FCR to act as antagonists during wrist flexion/extension, but as agonists during wrist radial deviation.41 The intricate interactions
of inhibitory interneurons and Renshaw cells on the spinal control of human wrist muscles undoubtedly illuminates the complexity of wrist neuromuscular control.

Wrist Proprioceptive Reflexes

Evidence of proprioceptive reflexes between wrist ligaments and forearm muscles has recently been presented.27 In this study, electrical stimulation of the dorsal SL interosseous ligament resulted in excitatory or inhibitory activation of wrist flexor and extensor muscles, occurring at specific time intervals.

The immediate reflex response occurred within 20 milliseconds after stimulation, and is thus equivalent to a monosynaptic or H-reflex, as described above. This reaction was consistently seen in the antagonist muscles of each wrist position, indicating a possible joint protective function. Hence, in wrist extension, radial and ulnar deviation, the immediate reactions were observed in FCR/FCU, whereas in wrist flexion, the first reaction was seen in extensor carpi radialis (ECR).

Later reactions, however, were predominately co-activations of the wrist flexors and extensors, that is, simultaneous excitation of FCR, FCU, and ECR, most likely intended to provide a global stability of the wrist joint (Figure 3). These reactions occurred from 50 to 150 milliseconds after stimulation, and are equivalent to the polysynaptic reflexes occurring at the spinal cord, with or without additional descending control.

From other joints, it is well recognized that a co-contraction of agonist and antagonist muscles around a joint will create a general joint stiffness, thereby effectively reducing the risk of joint damage.7,44,45 Co-activations are, however, not only important as a means to provide reflexive joint protection. The delicate balance of co-contraction is also believed important in maintaining smooth and even joint motions.46 This ability to sustain an adequate joint equilibrium has been shown to be impaired in patients with anterior cruciate ligament-deficient knees,47 where inadequate neuromuscular recruitment results in changes in knee kinematics that are potentially harmful to the joint.48 Similarly, an adequate proprioception re-education after wrist injuries should also entail an appropriate and balanced training of agonist/antagonist muscles, which will be covered in more detail below.

Supraspinal Reactions and Interactions

After local and segmental interactions in the spinal cord, afferent information from skin, joints, and muscles of the upper extremity are relayed via the spinocerebellar tract to the medulla, cerebellum, and via the dorsal column to the sensory/motor cortices.5 The complex action of the cerebellum is to integrate afferent information from the periphery with the processed information from the higher cortical areas, to coordinate and plan movements.49 Therefore, the cerebellum is the primary site for the generation of unconscious proprioception, which entails the neuromuscular control of a joint through reflex regulations as well as preprogramming of muscle stiffness in anticipation of coming motor actions.5,31,44

The afferent signals continue their path to the sensory and motor cortices, more specifically, to the S1, M1, and dorsal premotor cortex.50 The afferent signals from primarily muscle spindles and cutaneous receptors are here appreciated consciously as limb movement (kinesthesia) and limb position (joint position sense).51 These senses constitute the conscious proprioception, and will be discussed in greater detail below (Figure 4).

The Proprioception Senses and Therapeutic Applications

In summary, human proprioception comprises three major senses: kinesthesia, joint position sense, and neuromuscular control. Although the two former senses are appreciated and controlled consciously through cortical interactions, the latter is primarily un-/subconscious reflex control of a joint at the spinal and cerebellar level. Furthermore, although the conscious senses are primarily influenced by afferent information from muscle spindles and, to an extent, cutaneous receptors, the latter is in addition supported by information from intraarticular nerve endings.

The three major proprioception senses shall now be reviewed individually, and related to possible therapeutic applications in the rehabilitation of the wrist.
Kinesthesia

The term “kinesthesia” was first coined by Bastian, who in the late 19th century defined this as the ability to sense both position and movement of the limbs and trunk.52 This term hence referred to both kinesthesia and joint position sense (JPS). In a recent, excellent review of the “kinesthetic senses,” this concept of the two senses being one has now been laid completely to rest.53

Kinesthesia is thus a separate sense, constituting the ability to sense motion of a joint (or a limb). Thorough investigations have now proven that this sense is primarily influenced by the action of muscle spindles,51,54 with some contributions from skin receptors,22,57 thus limiting the sensitivity of the muscle spindle in detecting motion.

Skin receptors have been shown to be primarily of importance in the kinesthesia of finger joints,16 since the muscles controlling the fingers are located at a distance from the joint itself, in the forearm and hand. Joint receptors are similarly thought to be of importance whenever a muscle traverses more than one major joint,92 thus limiting the sensitivity of the muscle spindle in detecting motion.

The sense of kinesthesia is also distinctly influenced by vibration of tendons, as this will trigger muscle spindle afferents. Vibrations applied over tendons have, for instance, been shown to elicit illusory joint motions,58 as well as cortical changes in the areas related to kinesthesia.59 Vibration of a unilateral wrist extensor tendon has even been shown to cause bilateral kinesthetic illusions of wrist motion.60

In practice, the sense of kinesthesia is measured as the smallest change in joint angle needed to elicit a conscious awareness of joint motion, as related to time (∆/sec).61 The terminology frequently used in proprioception training is “threshold to detection of passive movement” or TTDPM.

From experience of using TTDPM in knee proprioception training, it has been suggested that the joint is placed at a certain angle and then moved passively and slowly, at a speed of 0.5 – 2 /sec, until the patient signals that limb motion occurs.62,63 Normal hand
isometric flexion/extension contractions cause 6–7° of perceived hand displacement, hence a speed of 0.5–2°/sec is by far within the normal range of perception.

Since limb movement is greatly influenced by visual cues, the patient should be blinded during testing (Figure 5). Furthermore, to adequately control the speed of joint motion and the degree of motion, it is advisable to use a professional training device, such as an Upper Limb Exerciser (Biometrics Ltd, Ladysmith, VA) or a Biodex Dynamometer (Biodex Medical Systems Inc., Shirley, NY).

**Joint Position Sense**

As outlined in the review by Proske and Gandevia (2009), JPS is thus a separate entity from kinesthesia. Although both are influenced by the action of muscle spindles, the central processing and interpretation of the two is separate. Furthermore, although tendon vibration has been shown to cause significant changes in the perception of kinesthesia, the same has not been shown for JPS. The sense of position is instead influenced by muscle command and muscle conditioning. For instance, conditioning of elbow flexors with one elbow flexed and elbow extensors with the other elbow extended, led to 20° errors in JPS matching of the two arms.

In proprioception training, JPS is defined as the ability to accurately reproduce a specific joint angle. This can be done either passively or actively, with visual cues or blinded. Passive JPS is when the therapist moves the wrist and the patient signals when the target position is reached. Active JPS is when the patient moves the wrist actively to the predetermined target position. It is advisable to start JPS training with visual cues, and progress to blindfolded exercises when the patient feels comfortable in the experimental setting. The results of JPS exercises are easily assessed using a goniometer to determine the accuracy of reproducing a specific joint angle (Figure 6). However, although easy to apply and assess, JPS has been criticized as a scientific technique because of its high inherent inter- and intraobserver variability and lack of reliability.

Despite this, the advantage of both JPS and kinesthesia in hand therapy practice is that any hand therapist with access to a goniometer can instruct and assess conscious proprioception re-education in a patient. Furthermore, these two conscious modalities of proprioception are well suited for the earliest stages of proprioception re-education, as they can be used in all stages of wrist rehabilitation without the risk of inducing harm.

**Unconscious or Neuromuscular Sense**

The unconscious proprioception sense, as mentioned above, comprises the neuromuscular sense. Pertaining to this sensation is the feed-forward anticipatory control of muscles around a joint, as well as the ability to unconsciously retain an adequate posture and maintain joint stability and equilibrium. The neuromuscular sense is greatly influenced by spinal reflexes for immediate joint control, as well as integrations in the cerebellum for planning, anticipating, and executing joint control. Hence, although the neuromuscular control of a joint is the hardest to objectively quantify or assess, it is likely of greatest importance in maintaining joint stability.

The purpose of a wrist neuromuscular rehabilitation program should be threefold: 1) to regain a smooth and balanced global motion of the wrist after trauma/surgery, 2) to use dynamic muscular compression to compensate a joint where the ligamentous restraints are inferior, and 3) to promote motion in muscles that are joint protective while avoiding activation of muscles that are potentially joint damaging.

The design of a detailed neuromuscular rehabilitation program is, thus, dependent on the type of wrist injury, the surgery performed, and the purpose of the rehabilitation regime. Presently, we lack substantial information with regard to the specific effects of wrist proprioceptive reflexes and subsequent neuromuscular actions on the wrist joint to be able to adequately design advanced programs. However, we may hypothesize on the types of exercises beneficial...
to wrist proprioception, both consciously and unconsciously.

**Types of Neuromuscular Rehabilitation**

Various types of exercises have been advocated in the neuromuscular training after ligament/joint injury. These include isokinetic, isometric, eccentric, co-activation, and reactive muscle activation exercises. Most of these therapies have been used after injuries to the knee or shoulder joints, but the terms shall now be explained in relation to wrist rehabilitation.

**Conscious Neuromuscular Rehabilitation**

The *isokinetic* exercises are most frequently used in proprioception training in athletes, as they are easy to instruct and assess using a commercial isokinetic exerciser (i.e., Biodex dynamometer). The term entails a muscle contraction performed at constant angular speed, and is thus independent of degree of muscle amplitude and velocity. It allows for a controlled training, enhances muscle strength throughout joint motion, and promotes endurance, but is in fact quite nonphysiologic as it does not reflect the actual daily activities of a muscle moving across a joint. Isokinetic training exercises have been shown to improve muscle strength, muscular endurance, and overall proprioceptive joint functions in athletes with ankle, knee, and shoulder instabilities. Hence, in the proprioception rehabilitation of a patient with extreme demands on wrist function, that is, a professional athlete or musician, it is likely to be of value to strengthen appropriate muscles and allow for an earlier return to training. In the common hand therapy setting, however, isokinetic exercises are likely to have a small role in basic wrist proprioception training, as it demands special equipment and knowledge, as well as being costly and time consuming.

The *isometric* exercise is when an active muscle contraction is performed at a fixed joint angle and, thus, with a constant muscle length. In contrast to isokinetic exercises, which are dynamic and throughout the range of joint motion, isometric exercises are static and serve to strengthen muscles at specific joint angles. They are, furthermore, easy to use, will quickly build muscle strength and are the type of exercise most frequently used in hand therapy training after carpal instabilities. Interestingly, unilateral isometric exercises of the wrist have been shown to increase voluntary muscle activation bilaterally, possibly by stimulating the motor cortex and descending neuromuscular control. Hence, the isometric exercises appear to have a key role in wrist proprioception re-education.

As isometric exercises are performed at specific joint angles, they can be used early after surgery without the risk of excessive joint motion, promoting early neuromuscular joint control. For instance, a controlled isometric activation of pronator quadratus in supination and neutral wrist position will serve to stabilize the distal radioulnar joint (DRUJ), and can be used both pre- and postoperatively in patients with triangular fibrocartilage complex (TFCC) injuries. Isometric exercises of the FCU, on the other hand, will act to compress the pisiform against the volar aspect of the triquetrum, which will likely contribute to a neuromuscular stability in the event of an ulnar midcarpal instability pattern.

Instability of the SL interval is one example of ligament injury; however, where isometric training may be either beneficial or harmful, depending on the degree of ligament injury. If the scapholunate interosseous ligament (SLIL) is intact, the FCR is thought to be an important dynamic stabilizer of the scaphoid, most likely through its compressive action on the STT joint. After a complete SLIL disruption with widening of the SL interval, however, the FCR cadaver studies of FCR kinematics have revealed a significant increase in moment arms, which will cause an increase in the load distribution through the radial carpus and contribute further displacement of the scaphoid when contracted. Hence, in a patient with partial SLIL injury or SL laxity, isometric FCR exercises would be beneficial through its stabilizing action on the SL interval. In a complete, untreated SLIL injury, however, FCR strengthening exercises would be detrimental and only serve to enhance SL instability.

**Eccentric** exercises are designed to strengthen the muscle while it is lengthened, usually because of an opposing load. The principle of eccentric training is most frequently used in the rehabilitation of chronic tendinopathies, where it is shown to significantly decrease pain and build tendon strength. As with the isokinetic exercises, it is in a dynamic action throughout joint motion that eccentric exercises are beneficial. In proprioception rehabilitation, however, the primary gain of eccentric training lies in the secondary concurrent effects on antagonist muscles. Eccentric exercises of wrist extensors have been shown to have an influence on the co-activation pattern of wrist flexors, which will undoubtedly influence the global stability of the wrist joint. After ligament injury, furthermore, periarticular muscles are frequently weak, which will result in a neuromuscular imbalance during concentric contractions. This effect reminds us of the delicate balance of wrist motion, where agonist and antagonist muscles constantly work in harmony to produce joint equilibrium.

**Co-activation** is the simultaneous contraction of agonist and antagonist muscles across a joint. As was shown in the first study of wrist proprioceptive reflexes, co-contractions of wrist flexors and extensors occurred as later onset reactions after stimulation of the SL ligament, most likely to produce a
global stability of the wrist. Co-activation exercises will, in hand therapy practice, demand the use of eccentric, concentric, and isometric exercises. One way to produce this, is by performing balance exercises with both hands on a ball, where slow and controlled motion of the ball on a table will allow the patient to simultaneously exercise flexors and extensors to produce a balanced wrist motion (Figure 7). Akin to the balance plate exercises used in ankle instabilities, which have been shown to greatly increase the proprioception and co-activation patterns around the ankle joint, these exercises will likely produce a re-education of wrist “balance.”

**Unconscious Neuromuscular Rehabilitation**

The mode of neuromuscular rehabilitation aimed at reconstructing the unconscious activation of muscles to restore joint balance is frequently used in proprioception rehabilitation of both the knee, ankle, and shoulder joints. This type of therapy has previously been referred to as “sensorimotor activation,” “perturbation training,” and recently, “reactive muscle activation.” This last phrase is precise in defining the nature of this rehabilitation regime, and will henceforth be used to describe the unconscious neuromuscular rehabilitation of the wrist. Reactive muscle activation (RMA) is probably the most difficult to apply in hand therapy, yet likely the most important in wrist proprioceptive function.

In essence, RMA aims at restoring the neuromuscular reflex patterns that exist in a normal joint and which have been shown to be disturbed in a ligament-deficient joint. By using perturbation exercises, such as the balance plate for ankle and knee injuries, RMA exercises are believed to restore the neuromuscular activation and, thus the electromyographic pattern, to the muscles around the joint.

The reflex patterns originating from the SLIL have now been delineated, and an interesting observation in this study was the consistent reflex inhibition of the ECU during ulnar deviation of the wrist. This pattern of inhibition differed greatly from the observations of co-contractions that were seen in other wrist positions. In a laboratory study on the role of muscles on carpal stability conducted by Salva and Garcia-Elias (unpublished material), contraction of the ECU was found to increase the pronation tendency of the distal row of the carpus by an average of 5°, which resulted in a widening of the SL interval and a tension of the SLIL. Hence, in patients with dynamic SL instability, a sudden contraction of the ECU may generate excessive torque at the midcarpal level, thus increasing the SL gap. This cadaver data may in fact explain why the ECU is inhibited during reflex stimulation of the SLIL.

Therefore, in the case of an SLIL injury, RMA training must serve to enhance those muscles protecting the SL joint (the FCU and ECRL, according to Salva and Garcia-Elias), while demoting activity in the potentially harmful ECU. This can be accomplished through reflexive plyometric exercises in an exercise machine, using the DTM. As DTM is a motion from extension-radial deviation to flexion-ulnar deviation, the SLIL friendly muscles will be exercised whereas the ECU will remain relaxed.

Another strategy that will possibly serve to stimulate RMA is the use of a so-called Powerball (NSD Powerball, RPM Sports, Tipperary, Ireland). The Powerball is a type of gyroscope using centrifugal forces to generate inertia and thus exercise the muscles acting on the wrist joint (Figure 8). A pilot study on the use of Powerball in healthy subjects...
revealed a significant increase in muscle endurance, but not muscle grip strength, over a four-week period of training. However, the true benefit of the Powerball lies most likely in the multidirectional motion generated by the gyroscope, which demands a reflex activation of the wrist muscles and an unconscious activation of both agonist and antagonist muscles. Additionally, this instrument is easy for the patient to use at free will and may thus promote an adherence to RMA training.

Influence from Other Sources on Proprioception

The influence from muscle spindles, cutaneous receptors, and joint afferents has been covered in detail above. These undoubtedly constitute the essence of proprioception as related to sensorimotor joint control. However, other sources may also contribute to the conscious appreciation of proprioception, and these deserve to be mentioned briefly as they may also contribute to the rehabilitation strategies used in proprioception re-education of the wrist.

Visual Influence

The impact of visual influence on the appreciation of kinesthesia is significant and even the illusion of a moving hand will generate cortical activations as seen during actual hand motion. This fact can be used as an adjunct to the kinesthesia and JPS training described above. The easiest way to integrate this into daily hand therapy practice is through the use of mirror therapy, which will create an illusion of motion and function in a damaged hand (Figure 9). Mirror therapy has been shown to enhance both sensory and motor recovery after injury. Furthermore, the observation of wrist motion will not only create an illusion of kinesthesia in an injured wrist but even stimulate activity in the somatosensory cortex, which will likely contribute important cortical control to enhance a functional proprioception re-education.

Cutaneous Influence

The role of skin receptors in finger joint kinesthesia, and in conscious proprioception as a whole, has been discussed previously. However, the negative impact of skin sensation has not been discussed. As the skin sensation of the hand has a powerful cortical representation, it may, theoretically, act to suppress information from afferents within the wrist joint, thus inhibiting an unconscious neuromuscular control. Previous authors have suggested the fitting of a pneumatic sleeve across a joint where kinesthesia and JPS is to be studied, to reduce the influx from cutaneous afferents. However, this may influence the patient’s ability to accurately move the joint, and is difficult to perform in a regular hand therapy setting. Therefore, a plausible alternative to the pneumatic sleeve may be local skin desensitization.

Recent studies on the role of cutaneous afferents in nerve regeneration have revealed fascinating results after desensitization of large skin areas. Patients with nerve injuries in the hand had a large cutaneous region desensitized using topical anesthetic cream on the volar aspect of the forearm. Using functional magnetic resonance imaging (fMRI), a rapid expansion of hand sensitivity in the contralateral somatosensory cortex could be seen. Hence, removal of cutaneous sensory stimuli in a healthy region was found to facilitate sensory re-education in a damaged region. Similarly, one may hypothesize that a cutaneous desensitization of the skin around the wrist would block cutaneous afferents, facilitate the afferent stimuli from articular mechanoreceptors, and, thus, enhance a proper proprioception re-education.

Conscious Appreciation of “Self”

The senses of proprioception not only include the awareness of limb movement/position and neuromuscular control, but also contribute to the complete conscious appreciation of “self.” Together with visual and tactile stimuli, proprioception is known to play an

![FIGURE 9. Mirror therapy to enhance proprioception awareness in a patient after wrist trauma/surgery. The patient positions the healthy wrist in front of the mirror (left image), to produce an illusion of motion in the injured wrist while trying to replicate the exercise behind the mirror (right image).]
important role in allowing an individual an adequate recognition of his or her physical body. After a wrist injury or wrist surgery, most patients have been immobilized during the posttraumatic or postoperative period. This period of immobilization removes not only the influx of afferent information from the wrist joint itself, but also from the skin, muscle spindles, and the visual awareness of the wrist. In short, the total conscious appreciation of the patient’s wrist is reduced. Hence, it is of importance to have a patient become consciously aware of his or her wrist joint and its function through so-called proprioception awareness. By creating an awareness of proprioception, it is hypothesized that the afferent pathways from the injured wrist may be re-established, with a subsequent long-term enhancement of unconscious proprioception. Indeed, as has been shown in the sensory re-education after nerve injuries, an early conscious appreciation of proprioception will likely serve to stimulate the cortical areas connected to sensorimotor joint control and possibly diminish the reorganizational changes observed in the cortex after nerve injury.

Protocol for Wrist Proprioception Rehabilitation

The review of proprioception senses and therapeutic applications above has largely been based on previous investigations conducted on the knee, ankle, and shoulder joints. Indeed, as written in the introduction, the concept of proprioception as related to wrist rehabilitation is in its cradle, and much clinical and basic science work remains to be done. With intent of providing a common foundation for wrist proprioception rehabilitation, a protocol is hereby provided to the reader (Table 2). This protocol still needs to be scientifically verified, and its presence in this review may appear premature. However, the purpose is to inspire practicing hand therapist to commence proprioception therapy and, perhaps, to do this on a common ground so that data may be compared. The protocol entails the proprioception senses and applications outlined in this review, and should be seen as a guideline to further clinical and scientific endeavors.

**CONCLUSION**

The aim of this review was to summarize the scientific evidence on wrist proprioception, and relate this to possible effects on wrist proprioceptive rehabilitation. The former is relatively easy, as it consists of collating previously known facts. The latter, however, is a venture into unknown reaches, equipped only with knowledge from other joints and experiences. The field of wrist proprioception and rehabilitation is vast, and we need a collective contribution and collaboration between surgeons and therapists to further our knowledge in this realm.

Further basic science studies are needed to investigate the existence of proprioceptive reflexes and the actual effect of specific neuromuscular actions on wrist stability. For instance, what part does the TFCC and DRUJ ligaments play in the integration of forearm/wrist motions? How do the important dorsal wrist ligaments contribute afferent information to the forearm motors? And what is the role of the nerves innervating the wrist joint, as compared with the possible role of cutaneous innervation, in wrist kinesthesia and proprioceptive feedback?

Clinical studies are needed to investigate the effect of proprioception re-education in patients and individuals with a high demand on wrist function in both preventing and rehabilitating wrist injuries. Furthermore, the development of adequate neuromuscular rehabilitation programs for the enhancement of proprioception re-education after wrist injuries, as well as in the intent of preventing injury, are needed. The first step to this may be through simple case reports (level IV studies) to share clinical experiences, with a progression to larger cohorts or even randomized clinical trials (level II-I studies).

The field of wrist proprioception and rehabilitation is vast, and we need a collective contribution and...
collaboration between surgeons and therapists to further our knowledge in this realm. As Nobel Laureate Santiago Ramón y Cajal wrote “everything discovered in a given domain is almost nothing in comparison with what is left to be discovered.”

REFERENCES


Joint position sense: The conscious sensation of joint position.

Kinesthesia: [Gr: kin- to move, -esthesia, to sense.] The conscious sensation of joint motion.

Ligamento-muscular reflexes: Reactions in muscles around a joint after influence by sensory information from joint ligaments.

Neuromuscular control: Unconscious activation of dynamic restraints occurring in preparation for and in response to joint motion and loading for the purpose of maintaining and restoring functional joint stability.

Proprioception: [Lat: proprio-, one’s own, -ception, to perceive.] Pertaining to the conscious and unconscious perception of movement, posture, and joint position.

Sensorimotor functions: The field of proprioception dealing specifically with joint control. The definition entails the total integration of sensory, motor, and central processes in relation to joint stability.

Systems: Organized groupings of related structures that perform certain common actions.
Record your answers on the Return Answer Form found on the tear-out coupon at the back of this issue. There is only one best answer for each question.

#1. Recent findings strongly suggest that proprioceptive properties within the wrist contribute to
   a. reduction of pain perception
   b. enhancement of pain perception
   c. neuromuscular control
   d. enhancement of grip strength

#2. The __________ is the predominant mechanoreceptor found in the wrist
   a. Ruffini ending
   b. Pacini corpuscle
   c. Meissner corpuscle
   d. Golgi-like receptor

#3. The greatest concentration of proprioceptive endings can be found in the ________ region
   a. palmar-ulnar
   b. dorsal-radial
   c. palmar-radial
   d. dorsal-ulnar

#4. The SC and STT ligaments are considered important in constraining and guiding the
   __________ during the Dart Throwers Motion
   a. lunate
   b. proximal pole of the scaphoid
   c. distal pole of the scaphoid
   d. waist of the scaphoid

#5. Primary motor control of the DTM is provided by the
   a. FCR and the ECU
   b. ECRB/ECRL and the FCU
   c. FCU and the ECU
   d. ECRB/ECRL and the FCR

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