J. Phys. Ther. Sci. 30: 734–740, 2018

The Journal of Physical Therapy Science

Original Article

Pinch aperture proprioception: reliability and feasibility study

Abdalghani Yahya, PT, MPT, DPT[1)], Timothy von Behren, DPT student[1)], Shira Levine, DPT student[1)], Marcio dos Santos, PT, MSc, PhD[1)*]

[1)] *Department of Physical Therapy and Rehabilitation Science, University of Kansas Medical Center: Mail stop 2002, 3901 Rainbow Boulevard, Kansas City, KS 66160, USA*

Abstract. [Purpose] To establish the reliability and feasibility of a novel pinch aperture device to measure proprioceptive joint position sense. [Subjects and Methods] Reliability of the pinch aperture device was assessed in 21 healthy subjects. Following familiarization with a 15° target position of the index finger and thumb, subjects performed 5 trials in which they attempted to actively reproduce the target position without visual feedback. This procedure was repeated at a testing session on a separate date, and the between-session intraclass correlation coefficient (ICC) was calculated. In addition, extensor tendon vibration was applied to 19 healthy subjects, and paired t-tests were conducted to compare performance under vibration and no-vibration conditions. Pinch aperture proprioception was also assessed in two individuals with known diabetic neuropathy. [Results] The pinch aperture device demonstrated excellent reliability in healthy subjects (ICC 0.88, 95% confidence interval 0.70–0.95). Tendon vibration disrupted pinch aperture proprioception, causing subjects to undershoot the target position (18.1 ± 2.6° vs. 14.8° ± 0.76, $p<0.001$). This tendency to undershoot the target position was also noted in individuals with diabetic neuropathy. [Conclusion] This study describes a reliable, feasible, and functional means of measuring finger proprioception. Further research should investigate the assessment and implications of pinch aperture proprioception in neurological and orthopedic populations.

Key words: Joint position sense, Index finger, Thumb

(This article was submitted Oct. 29, 2017, and was accepted Jan. 9, 2018)

INTRODUCTION

The awareness of position and movement of the body and its segments without visual cues is known as proprioception[1, 2)]. Proprioceptive feedback signals are collectively derived from mechanoreceptors—or "proprioceptors" as coined by Charles Sherrington more than 100 years ago[3)]—located in the skin, joints, ligaments, tendons, and muscle[4–7)]. The stresses or strains signaled by the mechanoreceptors travel through the peripheral nerves into the spinal cord to be processed in the central nervous system (CNS), which produce the sense of one's body position and movements[8)]. For instance, during an everyday task of object manipulation between the fingers, the proprioceptive feedback has a crucial role in the position of the arm, hand and fingers as well as guiding the movement from the starting to the ending points[9–11)]. In addition, grip force control studies suggest that proprioception is important for updating anticipatory or online commands to control for the magnitude of grip forces and the stability of joints[12)]. Hence, in the presence of proprioceptive deficits, manual activities that require fine finger movements and force are impaired. Such deficits can be the result of musculoskeletal injuries and neurological diseases affecting peripheral and central nerve structures like peripheral neuropathy, spinal cord injuries, multiple sclerosis, stroke, and others[13–21)].

A common clinical method used to measure finger proprioception, as part of peripheral neurological examination, is the

*Corresponding author. Marcio José dos Santos (E-mail: msantos@kumc.edu)

"up or down" test applied at the distal interphalangeal joint while the patient keeps his/her eyes closed[22]. Experimentally, proprioception in the index finger was investigated via a novel apparatus, which isolates the index finger, allowing full flexion and extension of the metacarpophalangeal joint while preventing the movements at the distal and proximal interphalangeal joints[23]. The ability to reproduce the desired position was measured by the difference between the finger positions with and without visual feedback[23]. The device used by these authors provides a quantitative measure of proprioception as compared to the traditional/clinical method, but still lacks the relevance to many functional tasks. For instance, these clinical or experimental methods for testing proprioception do not consider the complexity of natural grip function, which involves multiple fingers acting simultaneously during daily manual tasks, especially the pinch between index finger and thumb that are responsible for several fine motor skills. Recently, only one study has investigated proprioception between index finger and thumb using the finger active movement extent discrimination assessment (FAMEDA), which involved the subjects pinching a device with their index finger and thumb in the presence of a "stopping point" on five different predetermined aperture sizes[24]. Proprioception assessed through this method (i.e., using predetermined endpoints for the position of the joint based on signal detection theory) takes into account that the majority of decisions subjects make about the target endpoint are clouded with uncertainty[25–28]. Nonetheless, joint position reproduction, which requires the subjects to replicate a previously given position in space, is the most commonly test used in clinical sites[29]. In addition, it is still unknown whether the pinch movement proprioception (even the method aforementioned) is able to detect proprioceptive deficits. While hand proprioception deficits are common among people with musculoskeletal and neurological disorders[15, 18, 19], to our knowledge, no study has investigated pinch aperture proprioception using joint position reproduction sense. In this study, we defined pinch aperture as the distance between the thumb and index finger during the performance of movement towards one another as when executing a pinching grasp.

The pinch aperture proprioception is important to perform a variety of tasks such as buttoning a shirt, picking up small items, writing, and lifting objects with different weights. In fact, many studies have proposed the importance of proprioception in many manual tasks and its relevance in grip force control abilities[30, 31]. Therefore, there is a need for a reliable portable apparatus to measure pinch aperture proprioception. The purpose of this study is to test the reliability of a novel and simple device designed to measure pinch aperture proprioception. In addition, this device will be tested to detect potential proprioceptive deficits generated by vibration and neurological diseases. Our hypothesis is that the tested device will be reliable and able to detect proprioceptive impairments during vibration and in patients with neurological diseases.

SUBJECTS AND METHODS

A total of 21 healthy subjects (11 females and 10 males between 21 and 51 years) were recruited to test for the reliability of the new device and 19 subjects of those (11 females and 8 males between 21 and 51 years) were enrolled in the vibration study. We also tested 2 subjects (AJY and MJS) with diabetic peripheral neuropathy (DPN) as a result of type 2 diabetes (T2D), and two healthy matched for age, gender, and handedness (SRF and SJM). The demographic and clinical data for the DPN subjects and the healthy matched subjects are summarized in Table 1. The two subjects with DPN were screened for diabetes by using glycosylated hemoglobin (HbA1c) following the American diabetic association guidelines. The presence of neuropathy was confirmed using a battery of tests performed on the lower extremities that include the use of pinprick (tested using a safety pin), light touch (10 g monofilament), vibration using the on-off method (128 hz toning fork applied on the bony prominence of the big toe proximal to the nail bed), position sense of the big toe (up or down), bilateral knee and ankle reflexes (Taylor Percussion Reflex-Hammer), and temperature sensation (Darco Temp Touch)[32, 33]. In addition, subjects were asked about symptoms of pain, loss of balance, numbness, tingling, upper limb sensation, and general weakness. They were also tested for index finger and thumb sensation via Semmes-Weinstein monofilament examination (SWME) and 2-point discrimination (2PD) test, which confirmed decreased sensation in the upper limb as well. In addition, hand dexterity was assessed for the DPN subjects and the healthy control matched subjects using Moberg pickup test. All subjects were right handed (confirmed by the Edinburgh Inventory) with no history of hand injuries and showed no other pathological

Table 1. Clinical features

Groups	Age	BMI	HbA1c	2PD	SWME (g)	MPUT	Pinch aperture
Control							
SRF (female)	50	24.24	5.3	4	0.4	25.06	15 ± 0.6[a]
SJM (male)	51	24.11	5.1	5	0.16	24.89	15 ± 0[a]
Neuropathy							
AJY (female)	53	37.46	7.7	6	0.16	34.13	20.3 ± 1.5[a]
MJS (male)	55	23.62	6.5	6	0.6	45.8	20 ± 2.65[a]

BMI: body mass index; HbA1c: hemoglobin A1c; 2PD: 2-point discrimination; SWME: Simmes-Weinstin monofilament examination; MPUT: Moberg pickup test.
[a]Average and standard deviation from three trials.

conditions, except for the two diabetic patients with DPN. All subjects were volunteers and the informed consent was signed before data collection following the guidelines of the Human Subjects Committee at the University of Kansas Medical Center (STUDY00003358).

The device that we used to measure pinch aperture proprioception in this study was a lab-made device that includes a modified goniometer affixed on a cardboard box (4 × 17 × 10 centimeters; height, length, and width respectively). Two rounded pads were attached to both ends of the goniometer arms, which served as the subjects' index finger and thumb placement. The attachment between the box and the goniometer allows the fulcrum of the goniometer (along with his body) to move within a 1-inch distance to compensate for any angular movement of the moving fingers (Fig. 1).

A lab-made vibrator was used to disturb the proprioception of the thumb and index finger through the vibration of their extensor tendons. The vibrator consisted of 5 phone vibrators (DC3V/0.1A 1.5V/0.05A 10 × 2.7 mm Coin Mobile Vibration Motor) connected to universal AC plug-in Adapter (3-volt output, 30W power). This power allowed the vibrators to operate at a frequency of 100 hertz.

Subjects were asked to place the tips of their index finger and thumb along the perpendicular pads attached to the modified goniometer. Subjects placed their tested hand on the table and were asked to keep the wrist in a neutral position allowing their index and thumb fingers to move freely. First, subjects were familiarized with the device by letting them squeeze both arms of the modified goniometer throughout the full range using their index finger and thumb (pinch aperture) once. The full range of the device corresponded to 30° of maximal pinch opening (distance of 6.99 cm between the tip of index finger and thumb) to the complete closure (i.e., when one of the goniometer arms touched the opposing round pad). The test began with the examiner asking the subjects to close their eyes and positioned the device along with the subjects' fingers to the starting point, which was 30° of pinch aperture; subsequently, the examiner adjusted the arms of the goniometer to a 15° of pinch aperture (target point), which corresponded to a distance of approximately 3.5 cm between the index finger and thumb. The pinch apertures of 30° and 15° correspond with aperture sizes for holding a regular cup and a large medicine container, respectively. We have used just one testing target point in this study because past studies have shown this approach produces better validity and reliability of the measures[34, 35]. At the target position with eyes closed, the subjects were required to concentrate in this position and memorize the exact aperture size they were in. Thereafter, the examiner passively moved the goniometer arms along with the subject's fingers to the starting position of the test at 30°. During this maneuver, the subjects were instructed to follow the goniometer movement without resisting the pinch aperture. The subjects performed 2 memorization tasks to the target point (15°). Finally, the subjects were instructed to actively move the goniometer arms from the starting point back to the target point that was previously memorized (i.e., from 30° to 15°). Once they reached the memorized target, they were instructed to inform the experimenter by saying the word "here". Subjects were instructed to keep their fingers in contact with the perpendicular pads at all times during the testing session to allow for consistency of finger placements throughout the experiments.

For reliability assessment (experiment 1), the subjects performed 5 trials on the first day of testing and repeated 5 additional trials on a consecutive day under the same conditions.

For the disturbed proprioception via vibration (experiment 2), the identical experimental procedure described above was performed including the hand placement and starting (30°) to target point (15°) positions. The subjects were asked to perform 3 testing trials of matching the target under two experimental conditions: with and without vibration. Five vibrators were positioned as follows: 2 vibrators were attached over the extensor tendon of the index finger (approximately ¾ of an inch and 1 ¼ inch proximal to the first knuckle, respectively). In addition, 2 vibrators were positioned over the extensor pollicis longus tendon, one directly over the wrist joint and the other over the extensor pollicis longus tendon just below the metacarbophalangeal joint. The fifth vibrator was positioned over the extensor pollicis brevis and the abductor pollicis longus tendons, approximately over the wrist joint. The position of the vibrators was based on previous studies[36, 37]. An adhesive tape was used to fix the vibrators to the subjects' skin. Subjects were asked each time before the experiment if they felt any restrictions on the movement of their fingers, and if so, the tape was adjusted accordingly.

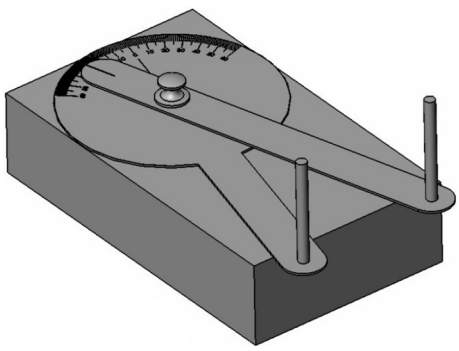

Fig. 1. Schematic representation of the pinch aperture proprioception device.

After the practice trial for familiarization and two practice trials for memorization as described above, vibration was turned on and subjects were asked to move the goniometer arms to the target endpoint. Vibration was applied for thirty seconds prior to moving the goniometer arms to allow for the vibration to take effect. The subjects were then asked to confirm whether they could feel the vibration effect. The order of vibration and no vibration was randomly assigned between subjects. At least one minute of rest between the conditions (with and without vibration) was provided. A single examiner performed all experiments to eliminate potential variability between different testers.

The experiment with the two neurological patients (experiment 3) was used to determine whether our device has potential to detect changes in pinch aperture proprioception in neurologic patients. Subjects performed 2 practice trials with eyes closed and an additional 3 trials of testing using the same target point (15°). The examiner used the same procedures described above for familiarization, memorization and assessment trials.

The examiner wrote down, on an assessment sheet, all actual target angles reached by the subjects during all experiments and conditions. The principal outcome variable was the measured angles from the subjects' trials compared to the actual target position. All data were entered in an Excel spreadsheet for posterior analysis. For experiment 1, the average of all 5 trials performed each day was used to test for the reproducibility between day 1 and day 2 using the intra-class correlation coefficient (ICC) with a 95% confidence interval. To represent the agreement of the measurements from day 1 and day 2, a Bland-Altman plot was developed. The differences between percentages of day 1 and day 2 were plotted against the mean target reached by the subjects during the two consecutive days. This shows how far the subjects were from the target across the two days. All assumptions were met to construct a Bland-Altman plot which include no significant differences between the measurements on either day and the trend of the data above and below the mean difference line are not significantly different, indicating no proportional bias[38]. For experiment 2, the average of the 3 trials was used for each subject to compare the differences between vibration and no vibration. Paired sample t-test was used to test for the difference between these two conditions. Alpha was set at 0.05 significance level and SPSS 16.0 for windows (SPSS Inc., Chicago, IL, USA) was used for data analysis. For experiment 3, we provided the mean values of 3 trials for each of the subjects with DPN and the healthy matched subjects.

RESULTS

Experiment 1 (reliability). We used a two-way random effect model. The average measure intra-class correlation coefficient (95% confidence interval) between day 1 and day 2 was 0.88 degrees (0.70–0.95). This shows a very good to excellent reproducibility over a two-day period ($p<0.001$). Bland-Altman plot showed a small percentage of error between day 1 and day 2 (Fig. 2). The average percentage of error is less than 2 percent between day 1 and day 2.

Experiment 2 (vibration). Applying vibration over the extensor tendons of the index and thumb fingers elicited changes in the pinch aperture proprioception. Majority of the subjects undershot the target during the vibration conditions. Figure 3 shows the mean values reached by the subjects during vibration (18.1° ± 2.59) and no vibration (14.8° ± 0.76) conditions, which were statistically significantly different between both conditions ($p<0.001$).

Experiment 3 (neurological subjects). Table 1 shows the clinical evaluation results for the two subjects with DPN (AJY and MJS) and the two healthy controls (SRF and SJM). Both subjects with DPN undershot to the target with an average of 20.17° while the two healthy control subjects matched the target with an average of 15°. In comparison, the entire healthy control group who participated in the second experiment had an average of 14.8° without vibration.

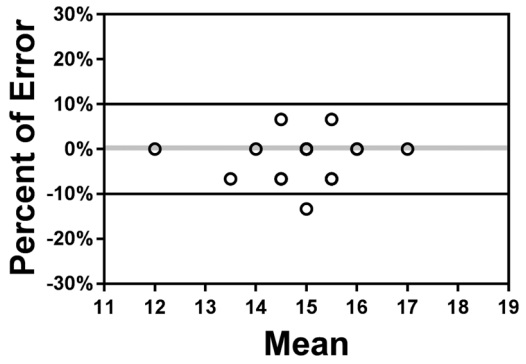

Fig. 2. Bland-Altman graph of pinch aperture proprioception (n=21). The grey line represents the target value with no error (0%). The black lines represent the percentage error (± 10%) from the target value. The values on the x-axis represent the average reproduced pinch aperture proprioception measurements between day 1 and day 2.

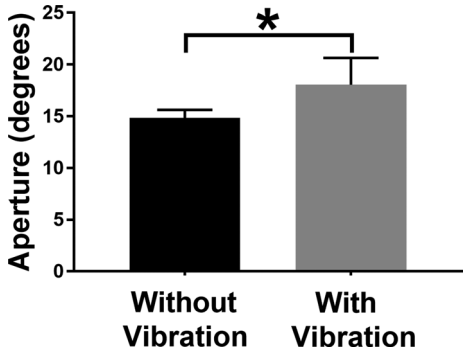

Fig. 3. Means and standard deviations for the pinch aperture proprioception during the pinch tasks with and without vibration (n=19). *Denotes significant differences ($p<0.001$) between the conditions.

DISCUSSION

This study is the first to examine pinch aperture proprioception between the index finger and the thumb in a functional and clinically accessible way using the joint position reproduction. Our findings confirmed our hypothesis that our novel and simple device will show high reliability and has the potential to capture changes in pinch aperture due to proprioceptive disruption (vibration) and in patients with neurological diseases. In addition, our methods for this specific test are easy to follow, practical and quick to apply, taking approximately 5 minutes to perform under normal conditions.

The reliability study we conducted to test our device showed moderate to excellent reproducibility for the pinch aperture proprioception over two consecutive days. Similar reliability was observed in other studies investigating proprioception in the index finger only or between the index finger and thumb. For instance, Wycherley and his colleagues[23] measured proprioception of the index finger, specifically the metacarpophalangeal joint position sense over three consecutive days in a control group of 12 healthy subjects. The ICC (95% CI) was 0.96 (0.90–0.98) between days 1 and 2, 0.86 (0.67–0.94) between days 2 and 3, and 0.92 (0.85–0.96) between all days. In the present study, we had a larger sample size (21 subjects) and the ICC between days 1 and 2 was 0.88 (0.70–0.95). In Addition, the Bland-Altman plot (Fig. 2) shows that the healthy subjects had a low percentage of error (less than ± 10%), and the mean values cluster around 15°. These are reasonable numbers that allow our device and methods to be used clinically[39].

Most of the previous studies have investigated proprioception of the proximal interphalangeal joint of the index finger[23, 40–43]. Although such investigations are important, they do not represent the complex nature of the grasping maneuvers involved in the majority of the manipulative tasks we perform during ADLs such as buttoning a shirt, holding a key, using a scissor, administering a medicine using an injection, and picking up pills. There is one study, however, that tested proprioception between the index finger and thumb which was termed as FAMEDA[24]. This study tested index finger and thumb "pinch movement discrimination" in 8 healthy subjects using a similar experimental set up. They asked the subjects to actively pinch with the index finger and thumb bringing the device arms together at 5 different stopping points. Subjects were provided with 15 practice trials with visual feedback while vision was occluded for the 50 testing trials. Although both studies by Han and his colleagues[24] and ours used different methods to test pinch aperture proprioception, the reliability values were higher in our study (i.e., the ICC was 0.85 between days 1 and 8 in their study while in our study the ICC was 0.88 between days 1 and 2). The principal difference between the methods of the study by Han et al.[24] and our study is that we used the joint position reproduction to test for proprioception, which is a common approach in clinical sites and only requires 3 to 5 repetitions to detect the position sense[29]. The method used by Han and his colleagues[24] was based on signal detection theory, which states that the majority of decisions we make are taken in the presence of some uncertainty, i.e., larger amount of trials is needed to establish certainty in the decision-making process about the aperture sizes being tested[27, 44]. In addition, they used the receiver operating characteristic (ROC) curve analysis to account for the probability of correct and wrong responses made by the subjects recalling the 5 different positions. In our study, we calculated for the average of 3 to 5 testing trials[45]. Furthermore, in our study, the practice trials were performed without visual feedback, while in the study by Han et al.[24] it was performed in presence of vision. It is known that vision contributes to the sense of proprioception and it can be argued that subjects might not have focused on the peripheral sense generated from muscle spindles and rather focused more on the central effort and the visual feedback fed into the internal model[46]. Finally, regardless of the two different techniques used, the results of both studies show that index finger-thumb aperture proprioception is reliable and both methods have potential to test the pinch aperture proprioception.

The purpose of the second experiment was to determine the feasibility of our device in detecting disruptions in pinch aperture proprioception via tendons' vibration. Goodwin and colleagues[7] were the pioneers in applying vibration to a muscle tendon to excite muscle spindles. As such, the signal carried through the Ia afferent nerve fibers will be interpreted in the CNS as an elongation in the muscle fibers[47, 48]. In the study by Goodwin et al.[7], the subjects experienced more elbow flexion movement due to the biceps vibration and the tracking forearm undershot the target when trying to keep both forearms parallel to each other. In addition, vibration to the tibialis anterior/soleus muscles produced a lengthening of the stimulated muscles perceived as plantarflexion/dorsiflexion, respectively[49]. Our findings agree with this previous research in which most of our subjects undershot relative to the target point when applying vibration to the tendons of thumb and index finger extensor muscles. Most importantly, our device and methods were able to detect such a disruption on the pinch aperture proprioception, which might facilitate the assessment of proprioception between the thumb and index finger. In addition, our apparatus and methods have greater potential to correlate its outcomes with outcomes of functional manual activities, which is our plan for future studies.

In addition to disrupted proprioception provoked by tendon vibration, our device and methods were able to detect proprioceptive deficits in two patients with DPN due to T2D. AJY and MJS exhibit profound deficits on the big toe during vibration and temperature testing. As compared to the healthy controls, both subjects also showed worse sensation on the hands (via SWME and 2PD tests), which was consistent with DPN. Furthermore, MJS showed deficits in the toe-up and down maneuver indicating proprioceptive deficits. Both subjects also performed the Moberg Pickup Test with eyes closed, which is known to test for proprioceptive deficits[30, 31]. In this test, subjects were asked to use the thumb and index finger when picking up the small items. Both subjects with DPN took a longer time to pick up small items as compared to the healthy matched

subjects. This could possibly be related to pinch aperture proprioception deficits. However, no study has investigated the relationship between Moberg Pickup Test and pinch aperture proprioception deficits. Future studies should further investigate this premise.

In conclusion, this study provides a simple, novel and clinical approach to test for pinch aperture proprioception. The device used by the present study has the potential to quantitatively and reliably measure pinch aperture proprioception deficits. This will help improve the diagnosis of hand and fingers proprioception and current rehabilitation programs dealing with hand function that requires a better understanding of the actual deficits. This may be critical for occupational and physical therapists when following up with a treatment strategy that focuses on improving proprioception of the hand and fingers. Future studies should investigate the reliability of the device between different therapists and in neurological and orthopedic population who have potential to exhibit pinch aperture proprioception deficits such as patients with Parkinson's, stroke, carpal tunnel syndrome, and hand osteoarthritis. Thus, our present device and methods can be used as another tool to measure proprioception in these subjects in the future. Finally, decrements in hand dexterity can be correlated with proprioceptive deficits affecting the pinch aperture, which must be the topic for future studies.

Conflict of interest

The authors report no conflict of interest.

REFERENCES

1) Lephart SM, Pincivero DM, Giraldo JL, et al.: The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med, 1997, 25: 130–137. [Medline] [CrossRef]
2) Röijezon U, Clark NC, Treleaven J: Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions. Man Ther, 2015, 20: 368–377. [Medline] [CrossRef]
3) Levine DN: Sherrington's "The integrative action of the nervous system": a centennial appraisal. J Neurol Sci, 2007, 253: 1–6. [Medline] [CrossRef]
4) Proske U, Wise AK, Gregory JE: The role of muscle receptors in the detection of movements. Prog Neurobiol, 2000, 60: 85–96. [Medline] [CrossRef]
5) Gandevia SC, Refshauge KM, Collins DF: Proprioception: peripheral inputs and perceptual interactions. Adv Exp Med Biol, 2002, 508: 61–68. [Medline] [CrossRef]
6) Cordo PJ, Horn JL, Künster D, et al.: Contributions of skin and muscle afferent input to movement sense in the human hand. J Neurophysiol, 2011, 105: 1879–1888. [Medline] [CrossRef]
7) Goodwin GM, McCloskey DI, Matthews PB: Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception? Science, 1972, 175: 1382–1384. [Medline] [CrossRef]
8) Karagiannopoulos C, Michlovitz S: Rehabilitation strategies for wrist sensorimotor control impairment: from theory to practice. J Hand Ther, 2016, 29: 154–165. [Medline] [CrossRef]
9) Vaidya M, Kording K, Saleh M, et al.: Neural coordination during reach-to-grasp. J Neurophysiol, 2015, 114: 1827–1836. [Medline] [CrossRef]
10) Rouse AG, Schieber MH: Spatiotemporal distribution of location and object effects in reach-to-grasp kinematics. J Neurophysiol, 2015, 114: 3268–3282. [Medline] [CrossRef]
11) Sartori L, Straulino E, Castiello U: How objects are grasped: the interplay between affordances and end-goals. PLoS One, 2011, 6: e25203. [Medline] [CrossRef]
12) Pilon JF, De Serres SJ, Feldman AG: Threshold position control of arm movement with anticipatory increase in grip force. Exp Brain Res, 2007, 181: 49–67. [Medline] [CrossRef]
13) Hincapie OL, Elkins JS, Vasquez-Welsh L: Proprioception retraining for a patient with chronic wrist pain secondary to ligament injury with no structural instability. J Hand Ther, 2016, 29: 183–190. [Medline] [CrossRef]
14) Sousa AS, Leite J, Costa B, et al.: Bilateral proprioceptive evaluation in individuals with unilateral chronic ankle instability. J Athl Train, 2017, 52: 360–367. [Medline] [CrossRef]
15) van Deursen RW, Simoneau GG: Foot and ankle sensory neuropathy, proprioception, and postural stability. J Orthop Sports Phys Ther, 1999, 29: 718–726. [Medline] [CrossRef]
16) Perreault EJ, Crago PE, Kirsch RF: Postural arm control following cervical spinal cord injury. IEEE Trans Neural Syst Rehabil Eng, 2001, 9: 369–377. [Medline] [CrossRef]
17) Bunday KL, Tazoe T, Rothwell JC, et al.: Subcortical control of precision grip after human spinal cord injury. J Neurosci, 2014, 34: 7341–7350. [Medline] [CrossRef]
18) van Deursen RW, Sanchez MM, Ulbrecht JS, et al.: The role of muscle spindles in ankle movement perception in human subjects with diabetic neuropathy. Exp Brain Res, 1998, 120: 1–8. [Medline] [CrossRef]
19) Simoneau GG, Derr JA, Ulbrecht JS, et al.: Diabetic sensory neuropathy effect on ankle joint movement perception. Arch Phys Med Rehabil, 1996, 77: 453–460. [Medline] [CrossRef]
20) Nowak DA, Hermsdörfer J, Topka H: Deficits of predictive grip force control during object manipulation in acute stroke. J Neurol, 2003, 250: 850–860. [Medline] [CrossRef]
21) Hermsdörfer J, Hagl E, Nowak DA: Deficits of anticipatory grip force control after damage to peripheral and central sensorimotor systems. Hum Mov Sci, 2004, 23: 643–662. [Medline] [CrossRef]
22) Moberg E: The role of cutaneous afferents in position sense, kinaesthesia, and motor function of the hand. Brain, 1983, 106: 1–19. [Medline] [CrossRef]
23) Wycherley AS, Helliwell PS, Bird HA: A novel device for the measurement of proprioception in the hand. Rheumatology (Oxford), 2005, 44: 638–641. [Med-

line] [CrossRef]
24) Han J, Waddington G, Anson J, et al.: A novel device for the measurement of functional finger pinch movement discrimination. Appl Mech Mater, 2011, 66: 620–625. [CrossRef]
25) Wixted JT, Stretch V: In defense of the signal detection interpretation of remember/know judgments. Psychon Bull Rev, 2004, 11: 616–641. [Medline] [CrossRef]
26) Galvin SJ, Podd JV, Drga V, et al.: Type 2 tasks in the theory of signal detectability: discrimination between correct and incorrect decisions. Psychon Bull Rev, 2003, 10: 843–876. [Medline] [CrossRef]
27) Heeger D: Signal detection theory. 1998.
28) MacMillan NA: Signal detection theory. Stevens' handbook of experimental psychology, 2002.
29) Clark NC, Röijezon U, Treleaven J: Proprioception in musculoskeletal rehabilitation. Part 2: Clinical assessment and intervention. Man Ther, 2015, 20: 378–387. [Medline] [CrossRef]
30) Moberg E: Objective methods for determining the functional value of sensibility in the hand. J Bone Joint Surg Br, 1958, 40-B: 454–476. [Medline]
31) Amirjani N, Ashworth NL, Gordon T, et al.: Normative values and the effects of age, gender, and handedness on the Moberg Pick-Up Test. Muscle Nerve, 2007, 35: 788–792. [Medline] [CrossRef]
32) Olaleye D, Perkins BA, Bril V: Evaluation of three screening tests and a risk assessment model for diagnosing peripheral neuropathy in the diabetes clinic. Diabetes Res Clin Pract, 2001, 54: 115–128. [Medline] [CrossRef]
33) Perkins BA, Olaleye D, Zinman B, et al.: Simple screening tests for peripheral neuropathy in the diabetes clinic. Diabetes Care, 2001, 24: 250–256. [Medline] [CrossRef]
34) Winter JA, Allen TJ, Proske U: Muscle spindle signals combine with the sense of effort to indicate limb position. J Physiol, 2005, 568: 1035–1046. [Medline] [CrossRef]
35) Walsh LD, Hesse CW, Morgan DL, et al.: Human forearm position sense after fatigue of elbow flexor muscles. J Physiol, 2004, 558: 705–715. [Medline] [CrossRef]
36) Collins DF, Refshauge KM, Todd G, et al.: Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee. J Neurophysiol, 2005, 94: 1699–1706. [Medline] [CrossRef]
37) Blanchard C, Roll R, Roll JP, et al.: Combined contribution of tactile and proprioceptive feedback to hand movement perception. Brain Res, 2011, 1382: 219–229. [Medline] [CrossRef]
38) Bland JM, Altman DG: Statistical methods for assessing agreement between two methods of clinical measurement. Lancet, 1986, 1: 307–310. [Medline] [CrossRef]
39) Gajdosik RL, Bohannon RW: Clinical measurement of range of motion. Review of goniometry emphasizing reliability and validity. Phys Ther, 1987, 67: 1867–1872. [Medline] [CrossRef]
40) Ferrell WR, Crighton A, Sturrock RD: Position sense at the proximal interphalangeal joint is distorted in patients with rheumatoid arthritis of finger joints. Exp Physiol, 1992, 77: 675–680. [Medline] [CrossRef]
41) Ferrell WR, Crighton A, Sturrock RD: Age-dependent changes in position sense in human proximal interphalangeal joints. Neuroreport, 1992, 3: 259–261. [Medline] [CrossRef]
42) Helliwell PS: Impaired proprioceptive acuity at the proximal interphalangeal joint in patients with the hypermobility syndrome. Br J Rheumatol, 1994, 33: 1192–1193. [Medline] [CrossRef]
43) Mallik AK, Ferrell WR, McDonald AG, et al.: Impaired proprioceptive acuity at the proximal interphalangeal joint in patients with the hypermobility syndrome. Br J Rheumatol, 1994, 33: 631–637. [Medline] [CrossRef]
44) Kellen D, Klauer KC, Singmann H: On the measurement of criterion noise in signal detection theory: the case of recognition memory. Psychol Rev, 2012, 119: 457–479. [Medline] [CrossRef]
45) Han J, Waddington G, Adams R, et al.: Assessing proprioception: a critical review of methods. J Sport Health Sci, 2016, 5: 80–90. [CrossRef]
46) Guerraz M, Provost S, Narison R, et al.: Integration of visual and proprioceptive afferents in kinesthesia. Neuroscience, 2012, 223: 258–268. [Medline] [CrossRef]
47) Burke D, Hagbarth KE, Löfstedt L, et al.: The responses of human muscle spindle endings to vibration of non-contracting muscles. J Physiol, 1976, 261: 673–693. [Medline] [CrossRef]
48) Roll JP, Vedel JP, Ribot E: Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. Exp Brain Res, 1989, 76: 213–222. [Medline] [CrossRef]
49) Wierzbicka MM, Gilhodes JC, Roll JP: Vibration-induced postural posteffects. J Neurophysiol, 1998, 79: 143–150. [Medline] [CrossRef]