




Clinical Assessment of Pain and Sensory Function in Peripheral Nerve Injury and Recovery: A Systematic Review of Literature

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Abstract

Peripheral nerve injuries (PNIs) often present with variable symptoms, making them difficult to diagnose, treat, and monitor. When neurologic compromise is inadequately assessed, suboptimal treatment decisions can result in lasting functional deficits. There are many available tools for evaluating pain and functional status of peripheral nerves. However, the literature lacks a detailed, comprehensive view of the data comparing the clinical utility of these modalities, and there is no consensus on the optimal algorithm for sensory and pain assessment in PNIs. We performed a systematic review of the literature focused on clinical data, evaluating pain and sensory assessment methods in peripheral nerves. We searched through multiple databases, including PubMed/Medline, Embase, and Google Scholar, to identify studies that assessed assessment tools and explored their advantages and disadvantages. A total of 66 studies were selected that assessed various tools used to assess patient's pain and sensory recovery after a PNI. This review may serve as a guide to select the most appropriate assessment tools for monitoring nerve pain and/or sensory function both pre- and postoperatively. As the surgeons work to improve treatments for PNI and dysfunction, identifying the most appropriate existing measures of success and future directions for improved algorithms could lead to improved patient outcomes.

Keywords

- ▶ peripheral nerve injuries
- ▶ peripheral nerves
- ▶ recovery of function
- ▶ treatment outcomes
- ▶ sensation

Peripheral nerve injuries (PNIs) continue to present challenges for surgeons, and multiple novel techniques and products have been utilized to address shortcomings of nerve repair.^{1–3} Pain and/or sensory deficits often develop after traumatic PNI or nerve surgery.⁴ In traumatic PNIs, surrounding tissue damage is common and has been associated with suboptimal outcomes.^{5,6} While treatment decisions in more severe injuries

may be relatively straightforward, incomplete transections or nervous deficiency not caused by trauma can be difficult to diagnose, treat, and monitor given due to subtle symptoms and/or slow progression to functional deficits. If nerve function is not accurately assessed, diagnosis may be delayed or overlooked and could result in long-lasting functional deficits with impaired quality of life.^{7–9}

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As understanding of nerve regeneration has improved, so have methods for evaluating nerve status both pre- and postoperatively. Given that nerve assessment algorithms can impact diagnosis, intervention, and recovery, a comprehensive view of the relevant literature may ultimately assist surgeons in improving patient outcomes.

Methods

Development Process

The authors performed a systematic review across multiple databases using a comprehensive combination of keywords and search algorithm according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines.¹⁰ The literature search focused on clinical data regarding the assessment of sensory and pain recovery after PNI was undertaken to define the utility of each assessment tool.

Literature Search

A systematic literature review was conducted to identify study abstracts for screening. The databases used included PubMed/Medline, Embase, Cochrane, and Google Scholar databases using the controlled terms: “Humans” and “Peripheral nerve injuries” and “sensory” or “pain” or “function” or “assessment” or “recovery” or “outcome.” Manual additions to our search query were made using the key terms: “sensory recovery,” “sensory outcomes,” “sensory assessment,” “sensory testing,” “sensation assessment,” “sensation assessment,” “nerve assessment,” “nerve sensory testing,” “sensory function testing,” and “nerve evaluation.” Search dates were from January 1960 to December 2020.

Study Eligibility

A minimum of two reviewers worked independently to further review and screen abstracts and titles. All articles that reported pathogenesis of sensory deficits secondary to nerve damage and those that assessed various tools used to measure sensory recovery and pain assessment tools were included. Only articles in English were reviewed. Full-text articles were assessed during screening if there was uncertainty on whether the article should be included. Article titles and abstracts that did not address our research question objective were excluded. Further full-text assessment of the selected articles was done, and articles that did not address peripheral nerve motor assessment and recovery were excluded. The PRISMA diagram in ► **Fig. 1** further describes the literature evaluation process.

Data Extraction

After assessment of eligibility, three authors extracted data from the marked articles. Important parameters that were recorded when available included the year of the study, number of patients in the study, sensitivity and specificity of the tools assessed, benefits and limitations of tools assessed, opportunities for improvement, and clinical roles in nerve recovery assessment.

Overview

Degree of peripheral nerve recovery can be assessed by testing the patient's postinjury sensory, pain, and motor function. Due to the breadth of information in each of these categories, the scope of this manuscript is limited to the monitoring of sensory recovery and pain attenuation. When assessing for peripheral nerve recovery, it is an important factor that there are multiple different types of nerves in the human body that vary based on size, myelination, conduction velocity, and function with larger and more heavily myelinated neurons, providing faster conduction velocities and carrying different types of information than smaller, unmyelinated neurons.^{6,11} These nerves can carry information from mechanosensory organs found on nonhairy or glabrous skin, such as the Ruffini endings, Meissner corpuscles, Merkel discs, and Pacinian corpuscles, to provide sensory information about texture and shape.¹¹

Regardless of the types of receptors or nerve fibers, nerves can be damaged during trauma and are classed by Seddon based on the demyelination and the extent of damage incurred to various layers of the nerve sheath and connective tissues. The mildest forms of injury or neurapraxia are often inflammatory injuries whereby nerves are compressed or pulled by surrounding structures. Severe nerve injuries or neurotmesis can lead to complete damage of the nerve's function due to complete transection of axons.⁶

Pain Assessment Tools

Pain is a critical factor in any nerve treatment algorithm. Poorly controlled pain has been linked to poor outcomes and long-term disability.^{12,13} A study of 70 soldiers who had sustained combat-related injuries found that 23% of sidelined soldiers could have returned to active duty if not for nerve-related chronic pain that increased their disability rating.¹⁴

Patients with upper extremity (UE) nerve injuries often have high pain disability (Pain Disability Index [PDI]), UE disability (Disabilities of the Arm, Shoulder, and Hand [DASH] questionnaire), and illness intrusiveness (the Illness Intrusiveness Rating Scale).¹⁵ The disability that arises from pain can also lead to higher rates of reactive depression.¹⁶

Numerical Rating Scale and Pain Visual Analog Scale

Aims/Advantages

The Numerical Rating Scale (NRS) and Visual Analog Scale (VAS) for pain are two methods of measuring patients' self-reported pain levels.^{17–19} Pain intensity, while important, is deficient without the context of the patient's pain tolerance. The VAS scale directs patients to indicate their pain on a 10-cm horizontal line between “no pain” and “worst imaginable pain” at the ends of the line. The distance between “no pain” and the patient's mark is recorded as patient's perception of pain.^{18,19} The NRS follows a similar method of identifying patient pain between “no pain” and “worst imaginable pain” but can be administered graphically or verbally. The VAS and



PRISMA 2009 Flow Diagram

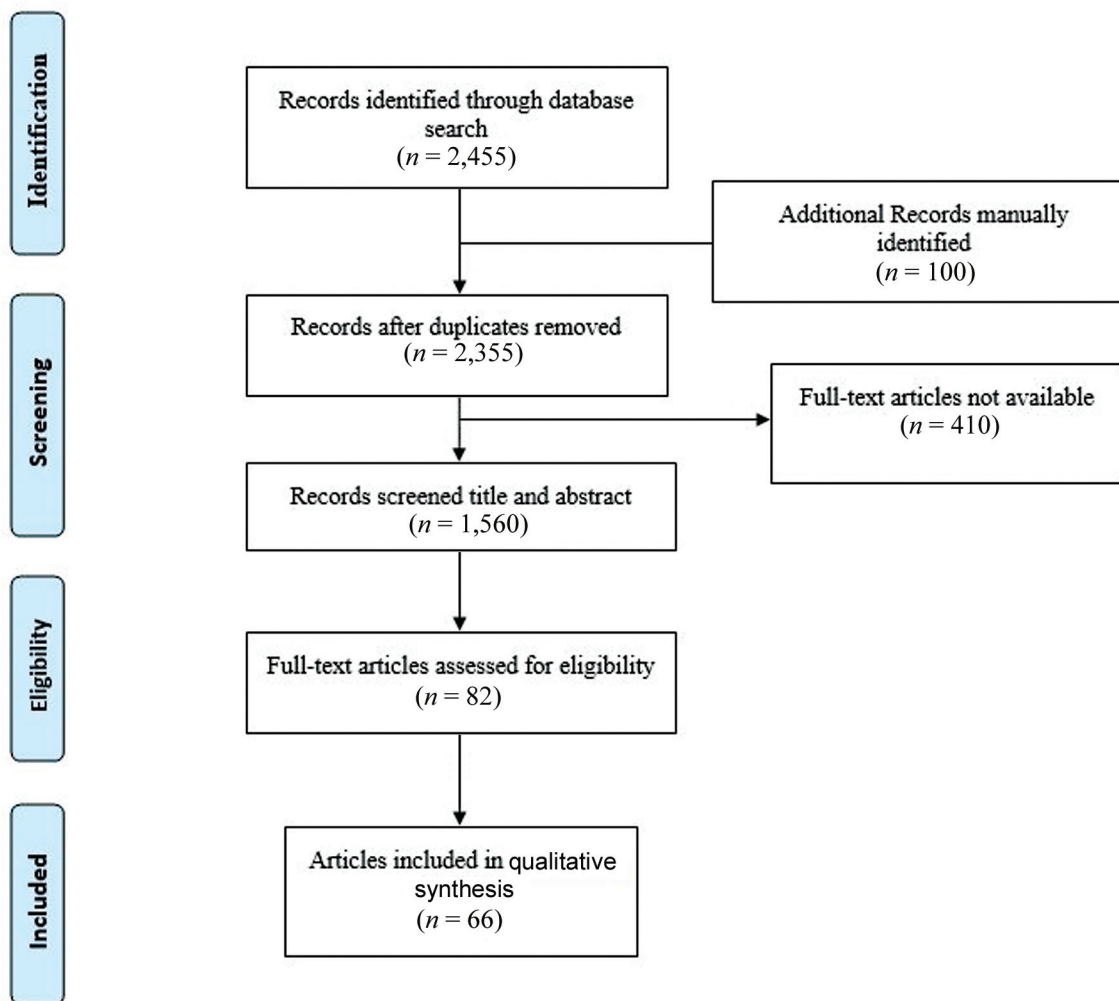


Fig. 1 PRISMA 2009 flow diagram. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-analyses.

NRS have excellent sensitivity and are reliable, with strong correlation between scores provided by the two tools.¹⁸

Disadvantages/Criticisms

These scales incorrectly assume that pain is a linear phenomenon. Furthermore, experience of pain varies between individuals.¹⁷ With respect to the VAS, patients who are cognitively impaired will not be able to provide an accurate assessment of their pain using the tool, and it has been shown that the majority of all patients (including unimpaired patients) do not prefer the VAS.¹⁸ Older patients, similarly, can have difficulty completing the VAS due to impaired motor skills. This scale can only be administered in person (not via telephone).^{19,20} While both tests help contextualize the pain intensity within what patients consider their uni-dimensional spectrum of pain, the tests do not convey information on the quality of the pain.¹⁹

Improvements

The labels on either end of the VAS test should be standardized as differing terminology can skew responses.²⁰ The NRS also requires further standardization as the test has been performed with differing numbers of stratifications (11, 21, or 101 levels).²⁰

Role in Nerve Assessment Algorithm

This tool should be used to identify patient-perceived pain intensity. Additional tools must be used to determine pain quality.

McGill's Pain Questionnaire and Short-Form MPQ

Aims/Advantages

The McGill's Pain Questionnaire (MPQ) incorporates sensory and pain response data, as well as pain intensity, to better understand the full spectrum of pain experienced by

patients.²¹ The questionnaire is a reliable and valid tool that can distinguish between nociceptive pain and neuropathic pain and is sensitive to the effects of nerve interventions.^{19,22}

Disadvantages/Criticisms

The length of the MPQ may place excessive burden on the respondent. The questionnaire also has complex vocabulary that can affect compliance.¹⁹ As a result, this test can be difficult to standardize among different clinics or hospital groups.^{17,19,22} Given its length, scoring of the MPQ can erroneously correlate quantity and quality such that high scores can be achieved with increased numbers of low quality responses.²² While the Short-Form-MPQ (SF-MPQ) is both easier to take and less complex to understand, it still requires supervision and familiarity with questionnaire terminology.¹⁹

Improvements

Criticisms of the MPQ resulted in the creation of the SF-MPQ. By reducing complexity and length, the SF-MPQ decreased respondent burden. Both the MPQ and the SF-MPQ can assess multiple types of pain but neither was designed to assess neuropathic pain.²³ To incorporate neuropathic pain characterization, SF-MPQ-2 was developed with seven domains for neuropathic pain. The SF-MPQ-2 is a reliable tool that has increased generalizability without increasing respondent burden.²³

Role in Nerve Assessment Algorithm

The MPQ is no longer recommended, as it has been succeeded by the SF-MPQ in understanding patient's dimensions of pain. This tool can be used to assess patient pain intensity, quality, and efficacy of treatment. The SF-MPQ-2 should be used when evaluating neuropathic pain.

Pain Disability Index

Aims/Advantages

The PDI is a 7-item questionnaire that assesses the extent to which pain interferes with patients' daily life activities (family and home responsibilities, recreation, social activity, occupation, sexual behavior, self-care, and life-support activity).²⁴ Each item is ranked on a scale of no disability (0) to total disability¹⁰ where disability is defined as limitations in fulfillment of a role that was once normal for that individual. The PDI has high internal consistency, sensitivity, modest test-retest reliability, and good concurrent validity.^{15,25,26} Scores can also indicate psychological distress and other pain-related disabilities.²⁵

Disadvantages/Criticisms

Pain behaviors (PBs) used in the PDI are not necessarily linked to disability.²⁵ Furthermore, there is a lack of standardization as some physicians use a one-factor PDI while others use a two-factor PDI.²⁶

Role in Nerve Assessment Algorithm

The brevity and reliability of the PDI places it ahead of more comprehensive tools such as the Sickness Impact Profile, Wet Haven Yale Multiaxial Pain Inventory, and Chronic Illness

Problem Inventory. However, it correlates well with the VAS tool. A one factor PDI may be used as an alternative to the VAS to understand both the intensity and the multidimensional experience of patients' pain.²⁶

Cold Intolerance Symptom Severity

Aims/Advantages

Cold intolerance, characterized by pain, stiffness, or altered perception with cold exposure, is a prevalent symptom in many UE PNIs and can present throughout a patient's recovery course.^{27,28} Using a cold intolerance severity scale, researchers have noted that 38% of patients with hand fractures are cold intolerant and that cold intolerance correlates with pain.¹⁶ While the pathophysiology of cold intolerance is not fully understood, the severity of cold intolerance may indicate poor nerve recovery.^{29,30} Unfortunately, patients do not report complete recovery from cold intolerance and may require lifestyle modifications.^{29,31,32}

The Cold Intolerance Symptom Severity (CISS) is a short questionnaire that assesses cold intolerance and how it affects daily function. Incidences of cold intolerance, sources of relief, and activities that may provoke cold intolerance are recorded using this questionnaire. The higher the score, the greater the cold intolerance. It is a highly reproducible and reliable test of cold intolerance in upper extremity injuries.^{12,29,31-34}

Disadvantages/Criticisms

The CISS is a broad assessment of cold intolerance that sacrifices a focus on symptom-specific minutia to maximize compliance.²⁹ The CISS does not accurately characterize the size of cold intolerant area, nor does it record how quickly symptoms of cold intolerance precipitate on cold exposure.³² Some have claimed that the grouping of the CISS scores into mild, moderate, severe, and extreme severe, is arbitrarily decided.³¹ Other critics of the CISS note that the test combines location, severity, and activity; however, these variables are not independent. Furthermore, the scoring system gives unwarranted emphasis to the answer option "Other" in Questions 2 to 4.^{32,34} The scoring system also gives more weight to activity impairments than symptom characteristics when determining overall score.^{32,34}

Improvements

Critics of the CISS have proposed that the inclusion of answer options "not applicable" and "never" in Questions 2 and 3.³¹

Role in Nerve Assessment Algorithm

The CISS may be used as a screening tool to identify pathologic cold intolerance.³¹

Patient-Reported Outcome Measurement Information System Pain Intensity

Aims/Advantages

The Patient-Reported Outcome Measurement Information System (PROMIS) Pain Intensity form initially contained a

single item assessing a patient's average pain on a self-reported scale (1 = no pain and 10 = worst pain imaginable).^{35,36} The test has demonstrated excellent reliability and validity and can be used in a wide variety of clinical scenarios.³⁷

Disadvantages/Criticisms

The PROMIS Pain Intensity offers little improvement over the traditional VAS and/or NRS.

Improvements

A 3-item PROMIS Pain intensity form has been developed which includes ratings of worst pain and average pain in the past 7 days, as well as pain at the time of completing the questionnaire.³⁸

Role in Nerve Assessment Algorithm

The PROMIS Pain Intensity can be used replacing NRS or VAS to evaluate pain intensity and may be preferred when simultaneously tracking other PROMIS scores (e.g., behavior and interference).

Patient-Reported Outcome Measurement Information System Pain Interference

Aims/Advantages

The PROMIS Pain Interference form is a 9-item questionnaire developed to assess the degree in which pain negatively affects daily activities.^{35,39} The form has been well validated with high reliability and independence of individual items/questions.³⁹ Scores can be compared with a baseline of the uninjured general population.³⁹

Disadvantages/Criticisms

Validation studies were performed with a large range of individuals both healthy and with a variety of health problems.³⁹

Role in Nerve Assessment Algorithm

The PROMIS Pain Interference form may be used to assess the degree in which nerve pain is impacting patients' daily activities and relationships. While it has been used in some peripheral nerve surgery studies,^{40,41} more clinical data are needed to determine its place in a variety of nerve-related pathologies.

Patient-Reported Outcome Measurement Information System Pain Behavior

Aims/Advantages

The PROMIS PB form is a 39-item questionnaire designed to comprehensively assess the behaviors performed by patients who communicate their pain to others (e.g., verbal complaints, facial expressions, gestures, posture, and activity limitations).⁴² Responses may give insights into the intensity, cause, and coping mechanisms associated with pain, particularly in chronic conditions.⁴²

Disadvantages/Criticisms

The complete PROMIS PB form has high respondent burden, and all questions may not be relevant to a particular clinical scenario. It is unable to distinguish between acute and chronic pain which are considered unique experiences from a patient's perspective.⁴³

Improvements

The PROMIS-PB can be adapted to create a short form for a given clinical scenario.⁴²

Role in Nerve Assessment Algorithm

While other pain assessments may be more valuable for assessing efficacy of interventions, the PROMIS PB form may assist in guiding nonsurgical treatment of chronic neuropathic pain.

Patient-Reported Outcome Measurement Information System Neuropathic Pain Quality Scale

Aims/Advantages

The Neuropathic Pain Quality scale (PROMIS-PQ-Neuro) is a 5-item questionnaire developed specifically to assess the quality of neuropathic pain (as opposed to nociceptive pain).³⁸ It has good sensitivity and specificity and can be used to differentiate between neuropathic and nonneuropathic pain.³⁸

Disadvantages/Criticisms

The PROMIS-PQ-Neuro was validated in patients with chronic conditions including osteoarthritis, rheumatoid arthritis, diabetic neuropathy, and cancer chemotherapy-induced peripheral neuropathy.³⁸ Other PROMIS forms have been developed to assess pain intensity, interference with daily activities, and behaviors expressed when in pain.^{39,42,44} These were also developed and validated in patients with chronic conditions unrelated to peripheral nerve dysfunction.

Role in Nerve Assessment Algorithm

While the PROMIS-PQ-Neuro is a reliable test for assessing pain quality, further clinical data are needed to determine its role in the context of peripheral nerve assessment.

Sensory Testing

In a clinical setting, sensation includes not only receptor detection of physical stimuli but also cortical mapping of inputs. Sensory impulses can be modulated via receptor field size and number. Furthermore, these receptors can be identified as quick or slow adapting.⁴⁵ While sensation is the subjective experience of stimuli, sensibility is the capacity to appreciate these stimuli.⁴⁶ Sensory testing most often measures sensation, and multiple tests can be used to address different parameters, including fast- or slow-acting receptors, innervation density, and/or distal versus proximal location of neurologic compromise.^{45,47} A comparison of common sensory testing modalities is presented in ▶ **Table 1**.^{48–55}

Table 1 Sensory testing normal values

Test	Description	Areas of use	Normal values	Additional information	Reference
Static 2-point discrimination	Minimum distance at which two points can be discriminated using the weight of the caliper alone	Skin, most accurate at fingertips and tongue. Specific areas often tested include palmar pad to the base of the index finger	Normal: <6 mm	10–19 years—men (6.1 mm ± 2.7), women (6.5 mm ± 2.5) 20–29 years—men (6.7 mm ± 2.5), women (7.5 mm ± 4.0) 30–39 years—men (7.2 mm ± 3.6), women (7.6 mm ± 3.1) 40–49 years—men (7.9 mm ± 2.6), women (8.1 mm ± 3.1) 50–59 years—men (8.8 mm ± 4.9), women (9.0 mm ± 3.4) 60–69 years—men (9.3 mm ± 3.8), women (9.3 mm ± 3.7) 70–79 years—men (9.1 mm ± 2.7), women (10.9 mm ± 4.8) Fair: 6–10 mm Poor: 11–15 mm	48–50
Moving 2-point discrimination	Discrimination between two moving calipers over the skin surface	Fingers (index or little finger)	Normal: <3 mm	Good: 4–7 mm Fair: 8–15 mm Poor: > 15 mm	30
Semmes-Weinstein monofilament test	Used to evaluate cutaneous pressure thresholds. Detection threshold defined as perceived sensation after application of the smallest S/W monofilament at the affected fingertip	Skin, hands	2.83 filament (filament no. 5)	3.61 filament (filament no. 4) = diminished perception of light touch 4.31 filament (filament no. 3) = diminished protective sensation 4.56 filament (filament no. 2) = loss of protective sensation 6.65 filament (filament no. 1) = loss of perception of deep pressure >6.65 filament (filament no. 0) = untestable (no response)	17,73
Pick-up test	Patients are timed as they pick up objects and place them in a container while blindfolded	Hands	Dominant hand (eyes open)—13 s Nondominant hand (eyes open)—13.4 s Dominant hand (eyes closed)—23.9 s Nondominant hand (eyes closed)—24.4 s	Eyes open/dominant hand—young ^{20–39} ; male (12.3 s), female (12.0 s) Eyes open/dominant hand—middle aged ^{40–59} ; male (16.5 s), female (12.6 s) Eyes open/dominant hand—old (60 +); male (16.8 s), female (16.0 s) Eyes open/nondominant hand—Young ^{20–39} ; male (14.0 s), female (12.5 s) Eyes open/nondominant hand—middle aged ^{40–59} ; male (18.0 s), female (13.3 s) Eyes open/nondominant hand—old (60 +); male (15.4 s), female (18.0 s)	49,51
Vibration assessment	Patients are touched with tuning forks of different frequencies to evaluate nerve damage	Skin on bony projections (interphalangeal joint of index finger, styloid)	6.0, upper extremity/ 4.0, lower extremity calibration setting	Upper extremity, <40 years: 6.5 Upper extremity, 41–85 years: 6.0 Upper extremity, >85 years: 5.5 Lower extremity, <40 years: 4.5	52,53,55,63

Table 1 (Continued)

Test	Description	Areas of use	Normal values	Additional information	Reference
Ten test	Examiners hand used to apply light touch and compare patient responses for affected and nonaffected hands	process, interphalangeal joint of the hallux, and internal malleolus)	10 points	Lower extremity, 41–60 years: 4.0 Lower extremity, 61–85 years: 3.5 Lower extremity, >85 years: 3.0 Vibration threshold values were obtained from the Rydel–Seiffer tuning fork calibration settings	54
Shape texture identification test (STI)	Differentiation between different textures with patients wearing earmuffs to eliminate auditory input. Differentiation between small, easily manipulated, three-dimensional shapes	Hands	6 points	Difficult to assess normal in children under the age of 5 years. Assessment scale was a 10 point analogue scale that rated sensibility of the test digit such that 1 represents lack of sensibility, 10 is normal Three points assigned for shape identification and 3 for texture	55,63
Manual tactile test	Assesses patients' ability to discern the weight (barognosis), roughness (roughness discrimination), and shape (stereognosis) of an object using active touch of the hand	Hands	Barognosis (2.66 s), roughness discrimination (33.04 s), stereognosis (28.05 s)	Barognosis—(18–35 years): 2.03 s ± 0.38 Barognosis—(36–55 years): 2.29 s ± 0.35 Barognosis—(>56 years): 2.97 s ± 0.6 Roughness discrimination—(18–35 years): 26.63 s ± 3.56 Roughness discrimination—(36–55 years): 29.4 s ± 3.43 Roughness discrimination—(>56 years): 35.78 s ± 6.42 Stereognosis—(18–35 years): 24.09 s ± 3.49 Stereognosis—(36–55 years): 25.91 s ± 2.54 Stereognosis—(>56 years): 30.2 s ± 4.20	88
Thermal sensitivity test	Tests ability to detect changes in temperature in the affected nerve distribution	Hands (index finger)	5 SD	<30 years: 4 SD 31–45 years: 4 SD 46–60 years: 6 SD >60 years: 9 SD Temperatures differences were set by manufacturer based on SD from normal (25°C)	55,74

Abbreviation: SD, standard deviation.

Two-Point Discrimination

Aims/Advantages

Developed in 1834 by E. H. Weber and refined in 1935 by Wilgis, the Two-Point Discrimination (2PD) measures the minimum distance between two stimuli at which a patient can correctly identify them as distinct points.^{46,56} The test is used to assess tactile discrimination and reveals the number of reinnervated receptors. Either one or two probes are applied to a surface with pressure that causes minimal discomfort, and patients are asked to report the number of probes that they can feel. The smallest distance that a patient can effectively discriminate between the two separate stimuli is recorded.

There are two types of 2PD, static and moving. Static 2PD measures density of the slow-adapting receptors as they reinnervate. Moving 2PD measures the quick-adapting receptors that recover sooner than other kinds of receptors.¹⁷ Researchers, using various health care workers and 2PD tests at two distances, demonstrated that similar 2PD results were measured across all observers and that the variability did not significantly affect its validity.⁵⁷

Disadvantages/Criticisms

While this measure is helpful in patients with acute, mild nerve injury, it may not be useful in patients with chronic or severe nerve injury, as the distance of discernment often is far greater than the width of a digit.^{45,58} Other criticisms of the technique include the lack of standardization of the force applied.^{28,45,59,60} Additionally, time between stimulus applications (from first to second point of 2PD) has been shown to affect the ability to discriminate between stimuli.⁶¹ While some have supported the 2PD test for its high level of consistency,⁶² others have considered it to be inherently inconsistent, largely due to the lack of control of application force, even within a single tester.^{60,63–66} Despite its widespread use, the 2PD has been shown to have low validity in assessing the tactile spatial acuity of hands.⁵⁸ The 2PD test also shows a lack of correlation or predictive value with commonly used electrodiagnostic techniques such as nerve conduction studies.⁶⁷ Perhaps most importantly, 2PD has been criticized for poor responsiveness which may be related to its use of passive rather than active touch (e.g., patients are touched by an object versus actively touching an object).^{28,68}

Improvements

One improvement of the 2PD test is the addition of orientation, resulting in a new two-point orientation discrimination (2POD) test.⁵⁶ This solves the problem of unintended non-spatial cues, an issue highlighted by critics who noted that at close distances, the brain may be able to detect a change in overall magnitude of pressure without truly detecting the two separate points of contact.⁶¹ By requiring the patient to specify the orientation (horizontal vs. vertical) of the second stimulus relative to the first, this false detection can be avoided.^{56,69} Spatial direction detection may also be enhanced using an adaptive stimulus.⁶⁹

Attempts to address the lack of applied force standardization in 2PD have resulted in multiple novel devices. These include the Absolute Digimatic caliper,⁵⁶ Dellon's Pressure-Specifying Sensory device,¹⁷ and the Disk-Criminator, the last of which has been shown to have good intertester reliability when used in a consistent manner.^{70,71}

Criticisms of the 2PD's passive touch limitation have led to alternative discrimination testing modalities such as tactile acuity charts (74). These consist of raised dots or rings on a sheet which patients must actively touch to discern multiple points at a variety of spacing intervals. Tactile acuity charts have demonstrated superior test–retest reliability over a 1-week period compared with passive measures.⁷²

Role in Nerve Assessment Algorithm

2PD is indicated for assessing tactile gnosis after nerve injury.⁷³ In a systematic review of peripheral nerve reconstruction functional outcomes, the most commonly used test was the static 2-point discrimination (S2PD) assessment for sensory assessment.⁶² Given its limitations, results of 2PD should be corroborated by other tests and/or clinical findings, especially when subjective recovery does not align with 2PD findings.

Semmes–Weinstein Monofilament Test

Aims/Advantages

Semmes–Weinstein monofilaments (SWM) assess cutaneous pressure threshold to reveal reinnervation status.¹⁷ The filament exerts a constant force on the skin area for approximately 1 second, and threshold is defined as the lightest filament that patients responded to correctly.⁵⁸ Results of SWM are superior to those attained from a tuning fork (detailed in a later section) as they provide stratified and quantitative measures that can be followed through the patient's recovery process.¹⁷ The test can also be used to identify sensory perception in all areas of the hand. It is a reliable, standardized, easily administered, and inexpensive method of obtaining quantitative sensory data.⁷³ Additionally, it has been shown to have significant associations with other evaluation tools, such as nerve conduction studies, particularly for carpal tunnel syndrome (CTS).⁷⁴ Unlike 2PD, the amount of force applied during SWM testing is controlled by the thickness of each filament.^{63,64}

Disadvantages/Criticisms

The SWM test is a fragile test due to its use of small filaments, and it is also limited by its use of an ordinal scale rather than a continuous scale.²⁸ Additionally, it has been criticized for its inability to account for variables outside of nerve injury that increase threshold, such as skin callouses and increased age.⁷⁵ The SWM test is more time-consuming than the 2PD which may make it less feasible in a busy office.^{76,77}

Improvements

The Weinstein Enhanced Sensory Test (WEST) is a more robust SWM test that focuses on consistent filament size across the filaments in a test kit. It also reports continuous

force values rather than ordinal values.²⁸ Furthermore, it demonstrates the best responsiveness in all sensory tests, especially in children, and is easily administered and scored in the clinical setting.⁵⁹

Role in Nerve Assessment Algorithm

SWM is indicated for assessing reinnervation after PNI.⁷³ It is often used alternatively to 2PD when there is adequate time in clinic to perform SWM.⁷⁶ Compared with 2PD, it has higher responsiveness to sensory function and can therefore be used to detect recovery sooner than 2PD.

Pick-Up Test

Aims/Advantages

Initially developed by Moberg⁷⁸ in 1958 and then quantified by Omer,⁷⁹ the Pick-Up test assesses general sensibility and tactile gnosis. In this test, patients are timed as they pick up an object and place it in a designated area while blindfolded. This test not only assesses whether the patient can sense the object but also if they can combine the sensory input with motion.⁴⁶ Compared with 2PD, the Pick-Up test has shown higher sensitivity to changes in patients with median nerve injury.⁶⁸

Disadvantages/Criticisms

The objects in this test have been specified as 10 small metal objects, but further specification does not exist. Without a standardized and/or commercially available set of metal objects for this test, clinicians must choose their own objects which adds heterogeneity between studies using this test.⁷⁸

Improvements

Standardization of the objects would improve the consistency of the Pick-Up test among clinicians.

Role in Nerve Assessment Algorithm

Since the 2PD test often does not detect early nerve recovery, the Pick-Up test may be used as a complement to the 2PD test, as it offers additional information to an examination in the early postoperative period. However, subsequent tests have been developed to fill this role (Shape Texture Identification [STI] test, detailed in a later section).

Vibration Assessment

Aims/Advantages

Vibration thresholds of fast-adapting receptors are tested using a tuning fork. A low-frequency fork can be used to assess early damage to nerves (especially after compression injury), as well as early recovery and reinnervation of previously damaged nerves.⁸⁰ Much like thermal sensitivity (discussed in a later section), fast-adapting fibers for vibration typically respond quickly to injury.⁴⁶ For chronic nerve compression, a higher frequency fork should be used.

Disadvantages/Criticisms

This test is highly subjective and based on patient recall. Tuning forks have been criticized for their low clinical value

due to shortcomings, including low interrater and intrarater reliability,⁸¹ variable application of force, and inconsistent performance of the fork due to the influence of the examiner's hand holding the instrument.⁶⁴

Improvements

While vibration thresholds are variable with tuning forks, vibration thresholds can be quantified using a Vibrometer. Vibrometers have fixed many of the problems associated with tuning forks, delivery is standardized with controlled frequency, intensity, and ramp speed.⁷⁵ The Vibratron II (fixed frequency 120Hz) has shown great intertester reliability.^{82,83} Still, these are relatively, uncommonly used in clinic for evaluation of nerve recovery after neurotmesis as they have been noted to be expensive and have been mainly studied in compression syndromes and vibration-induced neuropathy.⁸³

Though they are highly reliable, traditional vibrometers can only assess a single frequency and may not be able to address the full spectrum of nerve deficiency. Newer vibrometers include multiple vibration threshold frequencies.⁴⁵

Role in Nerve Assessment Algorithm (Recommendations for Appropriate Use)

Tuning forks have very limited indications for clinical use. Vibrometers may be used to detect early nerve injury in patients that may need surgery for nerve repair, especially following nerve compression or vibration-induced neuropathy.^{80,83}

Ten Test

Aims/Advantages

The Ten Test was initially described by Strauch et al as a quick and convenient way to assess light touch using an examiner's hand and patient's responses to the experience on a scale of 1 to 10, with 10 being normal.⁸⁴ This test compares touch on an affected limb versus that on the contralateral limb and can provide a quick screening of the large A- β nerve fibers.⁸⁴ It has good validity, reliability, and sensitivity, especially in CTS patients. In fact, it was found to be superior to the WEST and both forms of 2PD for detecting minimal loss of sensation in patients with CTS.⁷⁶ The Ten Test assesses patient perception of sensation on a scale of 0 to 10 and utilizes the healthy contralateral limb to understand sensory deficits.⁴⁵ This test can be used for adults and children over 5 years of age.^{54,59}

Disadvantages/Criticisms

The Ten Test is more subjective than most other sensation tests and has been criticized for lacking a standardized method to document hyperesthesia.^{76,85} Additionally, the test relies on one side of the body having full sensation. Many patients (especially older or diabetic patients) may be unaware of mild bilateral sensory loss which may confound results of this test.

Role in Nerve Assessment Algorithm

Clinicians may use the Ten Test to understand a patient's perceived discomfort and sensory changes after an injury.

These subjective findings represent one component of sensory function and should be corroborated by more objective measures when possible.⁵⁹

Shape Texture Identification Test (STI)

Aims/Advantages

The STI test uses multiple objects of varying size and shape that the patient has to identify. This test is particularly useful in median nerve injury patients as it requires active manipulation. The STI differs from other tactile gnosis tests in that it specifically focuses on identifying shapes, objects, and textures.⁵⁹ The active manipulation is a key feature of the STI test that makes it a valuable complement to 2PD which does not take into account active touch.⁶³ This test has shown high sensitivity and specificity for measurement of tactile gnosis at follow-up assessments following nerve injury.^{33,63,73} Unlike the previously described Pick-Up test, the STI is highly standardized.⁸⁶

Disadvantages/Criticisms

Although the STI test is standardized and existing reports have shown its validity, the literature for the STI test is limited, given its relatively recent development and less-frequent clinical use compared with tests such as 2PD and SWM.⁸⁷ At present, the STI is typically used as a complement to the 2PD test rather than a stand-alone measure of sensory recovery.

Role in Nerve Assessment Algorithm

The STI reliably detects change in previously injured nerve function and should be used as a complement or alternative to 2PD or SWM, particularly when these do not correlate with subjective findings. Further clinical data are needed to determine whether STI may replace 2PD or SWM in current assessment algorithms.

Manual Tactile Test

Aims/Advantages

The manual tactile test (MTT) was developed as a result of need to refine and interpret sensory information through self-generated movements with greater precision.⁸⁸ Additionally, active hand sensation can facilitate better predictions for hand performance than those of traditional sensibility assessments. The MTT is comprised of three subtests which assess patients' ability to discern the weight (barognosis), roughness (roughness discrimination), and shape (stereognosis) of an object using active touch of the hand.

The MTT was developed to incorporate both cutaneous pressure and kinesthetic impulses transmitted through the hand. Given that more types of sensory information are included, the MTT may provide more comprehensive data on tactile gnosis following nerve injury. Among sensory tests for peripheral nerves, the inclusion of barognosis is unique to the MTT and has shown utility in monitoring functional sensibility of neuropathic hands both pre- and postoperatively.⁵⁸

Disadvantages/Criticisms

The MTT is used primarily for patients with CTS. Since it requires the ability to manipulate the hand, the MTT cannot be executed with a patient lacking this capacity.⁵⁸ Although the test can be used to measure sensation in patients with CTS, it may not be superior to other, more commonly used sensory tests. In fact, Hsu et al found that both 2PD and SWM had better diagnostic power than MTT in CTS.⁸⁸ The test is currently lacking a measurement for tactile threshold sensibility which may need to be added if it is to stand on its own.

Role in Nerve Assessment Algorithm

The MTT has been used in determining the impairment of manual touch sensibility for CTS with high reliability, accuracy, and validity. In addition to its use for patients with CTS, clinicians have begun using the test to track age-related degradation in sensorimotor control of the hand in the elderly population, and to monitor nerve recovery after injury.^{58,88} While the SWM is currently considered a superior diagnostic tool, the MTT has been suggested as an adjunct to SWM in monitoring the progression of hand sensibility during the regeneration period.⁵⁸

Thermal Sensitivity Test (Excluding Cold Intolerance)

Aims/Advantages

The Thermal Sensitivity Test was first described as a method of assessing thermal discrimination in patients with diabetic peripheral neuropathy. Thermal sensitivity is reliant on small fibers which are usually the first to be damaged in diabetic neuropathy.⁸⁹ More recently, however, the Thermal Sensitivity Test was used in a study to assess recovery after complete nerve laceration (neurotmesis). The 2015 retrospective study showed a correlation between thermal sensitivity and mechanosensory function, as measured by 2PD test and Semmes-Weinstein test. However, recovery of temperature differentiation was demonstrated in approximately half of the patients in this study, while 17% had normal 2PD test and only 7% had normal SW monofilament test. These results indicate that thermal sensitivity is recovered prior to full recovery and may be a better indicator of return of protective sensation rather than full functional recovery.⁷⁴

Disadvantages/Criticisms

Although it correlates with better overall hand function, good temperature sensibility is seen in patients with poor touch sensibility as well. Therefore, the test may be a more sensitive but far less-specific measure of recovered hand function. Additionally, cold intolerance is thought to be a more determinant factor for hand function than temperature discrimination, and no significant relationship has been shown between these two variables.⁷⁴

Role in Nerve Assessment Algorithm

Although the Thermal Sensitivity Test correlates with overall hand function, it is less clinically relevant than touch sensibility. It is not currently used often for nerve assessment

following neurotmesis, although future studies may lead to increased usage of the assessment for this purpose, particularly in the early stages of recovery.⁷⁴

Discussion

Selecting the optimal nerve test(s) is difficult and lacks standardization across the field. While a battery of tests may be ideal, there are practical considerations that prevent surgeons from performing every test at each visit. Thus, it is important to optimize the assessment algorithm to obtain the most accurate and relevant data regarding each patient's unique presentation.⁹⁰

Pain can be assessed both via cold intolerance and traditional pain assessments. Of the cold intolerance tools, the CISS is recommended as a screening tool to identify pathologic cold intolerance. Of the other pain assessments, the NRS and VAS, while simple to administer, provide only one dimension of pain. A multidimensional approach using SF-MPQ or PDI is recommended. Of the two multidimensional assessment tools, the MPQ will characterize pain while the PDI will give insight into how pain is affecting daily life.

While 2PD is widely used for sensory assessment, it lacks responsiveness and may require either a complementary test or an alternative. The Pick-Up test, Thermal Sensitivity Test, or vibration assessment are good complements to the 2PD test when the 2PD is not responsive. Alternatively, one may choose to use the SWM instead of the 2PD. The SWM is the most responsive tool and has high reliability; however, it can be time-consuming and is not always practical. Additional tests may be utilized to add functional perspective, including the STI test or the MTT test. The Ten Test, though highly subjective, may be used when time or instrumentation is lacking, as it is a simple, rapid assessment.

Limitations

Further studies are encouraged to assess the necessity and ideal combination of tools when assessing peripheral nerve sensory recovery and pain management. When assessing peripheral nerve sensory recovery and pain assessment, the various combinations of tools and idiosyncratic administration methods can lead to heterogeneity when performing a literature review on this topic. Furthermore, there is a paucity of data regarding clinically relevant differences regarding pain scores before and after treatment for PNI. To further standardize sensory and pain assessments, there is a need for increased research in these areas.

Conclusion

Despite advances in diagnosis and treatment of PNIs, there remains no consensus on the optimal assessment algorithm. This review may serve as a valuable resource for surgeons determining the appropriate sensory and pain assessments to monitor nerve function both pre- and postoperatively.

Author Contributions

A.A.J.: conceptualization, investigation, project administration, and manuscript preparation. S.R.: investigation, and manuscript preparation. J.R.: investigation, and manuscript preparation. C.T.C.: conceptualization, project administration, and manuscript preparation. I.D.: supervision and validation. B.J.M.: conceptualization and validation.

Conflict of Interest

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References

- Papatheodorou LK, Williams BG, Sotereanos DG. Preliminary results of recurrent cubital tunnel syndrome treated with neurolysis and porcine extracellular matrix nerve wrap. *J Hand Surg Am* 2015;40(05):987–992
- Gaspar MP, Abdelfattah HM, Welch IW, Vosbikian MM, Kane PM, Rekant MS. Recurrent cubital tunnel syndrome treated with revision neurolysis and amniotic membrane nerve wrapping. *J Shoulder Elbow Surg* 2016;25(12):2057–2065
- Tos P, Crosio A, Pugliese P, Adani R, Toia F, Artiaco S. Painful scar neuropathy: principles of diagnosis and treatment. *Plast Aesthet Res.* 2015;2:156–164
- Bogle A, Wiesler E. Neuritis of the cutaneous nerves of the hand. *J Hand Surg Am* 2014;39(06):1204–1206
- Stassart RM, Fledrich R, Velanac V, et al. A role for Schwann cell-derived neuregulin-1 in remyelination. *Nat Neurosci* 2013;16(01):48–54
- Menorca RMG, Fussell TS, Elfar JC. Nerve physiology: mechanisms of injury and recovery. *Hand Clin* 2013;29(03):317–330
- Baltodano PA, Tong AJ, Chhabra A, Rosson GD. The role of magnetic resonance neurography in the postoperative management of peripheral nerve injuries. *Neuroimaging Clin N Am* 2014;24(01):235–244
- Martin Noguerol T, Barousse R, Gómez Cabrera M, Socolovsky M, Bencardino JT, Luna A. Functional MR neurography in evaluation of peripheral nerve trauma and postsurgical assessment. *Radiographics* 2019;39(02):427–446
- Alvites R, Rita Caseiro A, Santos Pedrosa S, et al. Peripheral nerve injury and axonotmesis: State of the art and recent advances. *Cogent Med* 2018;5(01):1466404
- Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Int J Surg* 2021;88:105906
- Wellnitz SA, Lesniak DR, Gerling GJ, Lumpkin EA. The regularity of sustained firing reveals two populations of slowly adapting touch receptors in mouse hairy skin. *J Neurophysiol* 2010;103(06):3378–3388
- Novak CB, von der Heyde RL. Evidence and techniques in rehabilitation following nerve injuries. *Hand Clin* 2013;29(03):383–392
- Novak CB, Anastakis DJ, Beaton DE, Katz J. Patient-reported outcome after peripheral nerve injury. *J Hand Surg Am* 2009;34(02):281–287
- Rivera JC, Glebus GP, Cho MS. Disability following combat-sustained nerve injury of the upper limb. *Bone Joint J* 2014;96-B(02):254–258
- Novak CB, Anastakis DJ, Beaton DE, Mackinnon SE, Katz J. Relationships among pain disability, pain intensity, illness intrusiveness,

- and upper extremity disability in patients with traumatic peripheral nerve injury. *J Hand Surg Am* 2010;35(10):1633–1639
- 16 Ring D. Symptoms and disability after major peripheral nerve injury. *Hand Clin* 2013;29(03):421–425
 - 17 Wang Y, Sunitha M, Chung KC. How to measure outcomes of peripheral nerve surgery. *Hand Clin* 2013;29(03):349–361
 - 18 Williamson A, Hoggart B. Pain: a review of three commonly used pain rating scales. *J Clin Nurs* 2005;14(07):798–804
 - 19 Hawker GA, Mian S, Kendzerska T, French M. Measures of adult pain: Visual Analogue Scale for Pain (VAS Pain), Numeric Rating Scale for Pain (NRS Pain), McGill Pain Questionnaire (MPQ), Short-Form McGill Pain Questionnaire (SF-MPQ), Chronic Pain Grade Scale (CPGS), Short Form-36 Bodily Pain Scale (SF-36 BPS), and Measure of Intermittent and Constant Osteoarthritis Pain (ICOAP). *Arthritis Care Res (Hoboken)* 2011;63(Suppl 11):S240–S252
 - 20 Hjermstad MJ, Fayers PM, Haugen DF, et al; European Palliative Care Research Collaborative (EPCRC) Studies comparing Numerical Rating Scales, Verbal Rating Scales, and Visual Analogue Scales for assessment of pain intensity in adults: a systematic literature review. *J Pain Symptom Manage* 2011;41(06):1073–1093
 - 21 Melzack R. The McGill Pain Questionnaire: major properties and scoring methods. *Pain* 1975;1(03):277–299
 - 22 Main CJ. Pain assessment in context: a state of the science review of the McGill pain questionnaire 40 years on. *Pain* 2016;157(07):1387–1399
 - 23 Dworkin RH, Turk DC, Revicki DA, et al. Development and initial validation of an expanded and revised version of the Short-form McGill Pain Questionnaire (SF-MPQ-2). *Pain* 2009;144(1-2):35–42
 - 24 Pollard CA. Preliminary validity study of the pain disability index. *Percept Mot Skills* 1984;59(03):974
 - 25 Tait RC, Chibnall JT, Krause S. The pain disability index: psychometric properties. *Pain* 1990;40(02):171–182
 - 26 Chibnall JT, Tait RC. The pain disability index: factor structure and normative data. *Arch Phys Med Rehabil* 1994;75(10):1082–1086
 - 27 Irwin MS, Gilbert SEA, Terenghi G, Smith RW, Green CJ. Cold intolerance following peripheral nerve injury. Natural history and factors predicting severity of symptoms. *J Hand Surg [Br]* 1997;22(03):308–316
 - 28 MacDermid JC. Measurement of health outcomes following tendon and nerve repair. *J Hand Ther* 2005;18(02):297–312
 - 29 Irwin MS, Gilbert SEA, Terenghi G, Smith RW, Green CJ. Cold intolerance following peripheral nerve injury. Natural history and factors predicting severity of symptoms. *J Hand Surg [Br]* 1997;22(03):308–316
 - 30 Carlsson IK, Dahlin LB. Self-reported cold sensitivity in patients with traumatic hand injuries or hand-arm vibration syndrome - an eight year follow up. *BMC Musculoskelet Disord* 2014;15(01):83
 - 31 Ruijs ACJ, Jaquet JB, Daanen HAM, Hovius SER. Cold intolerance of the hand measured by the CISS questionnaire in a normative study population. *J Hand Surg [Br]* 2006;31(05):533–536
 - 32 Davey H, Belcher H. Cold intolerance assessment: a reappraisal. *Hand Ther* 2014;19(02):40–46
 - 33 Fonseca MCR, Elui VMC, Lalone E, et al. Functional, motor, and sensory assessment instruments upon nerve repair in adult hands: systematic review of psychometric properties. *Syst Rev* 2018;7(01):175
 - 34 Carlsson I, Cederlund R, Höglund P, Lundborg G, Rosén B. Hand injuries and cold sensitivity: reliability and validity of cold sensitivity questionnaires. *Disabil Rehabil* 2008;30(25):1920–1928
 - 35 Reeve BB, Hays RD, Bjorner JB, et al; PROMIS Cooperative Group. Psychometric evaluation and calibration of health-related quality of life item banks: plans for the Patient-Reported Outcomes Measurement Information System (PROMIS). *Med Care* 2007;45(05, Suppl 1):S22–S31
 - 36 Broderick JE, Schneider S, Junghanel DU, Schwartz JE, Stone AA. Validity and reliability of patient-reported outcomes measurement information system instruments in osteoarthritis. *Arthritis Care Res (Hoboken)* 2013;65(10):1625–1633
 - 37 Cella D, Riley W, Stone A, et al; PROMIS Cooperative Group. The Patient-Reported Outcomes Measurement Information System (PROMIS) developed and tested its first wave of adult self-reported health outcome item banks: 2005–2008. *J Clin Epidemiol* 2010;63(11):1179–1194
 - 38 Askew RL, Cook KF, Keefe FJ, et al. A PROMIS measure of neuropathic pain quality. *Value Health* 2016;19(05):623–630
 - 39 Amtmann D, Cook KF, Jensen MP, et al. Development of a PROMIS item bank to measure pain interference. *Pain* 2010;150(01):173–182
 - 40 Mioton LM, Dumanian GA, Fracol ME, et al. Benchmarking residual limb pain and phantom limb pain in amputees through a patient-reported outcomes survey. *Plast Reconstr Surg Glob Open* 2020;8(07):e2977
 - 41 Dumanian GA, Potter BK, Mioton LM, et al. Targeted muscle reinnervation treats neuroma and phantom pain in major limb amputees: a randomized clinical trial. *Ann Surg* 2019;270(02):238–246
 - 42 Revicki DA, Chen WH, Harnam N, et al. Development and psychometric analysis of the PROMIS pain behavior item bank. *Pain* 2009;146(1,2):158–169
 - 43 Cook KF, Dunn W, Griffith JW, et al. Pain assessment using the NIH toolbox. *Neurology* 2013;80(11, Suppl 3):S49–S53
 - 44 Cook KF, Jensen SE, Schalet BD, et al. PROMIS measures of pain, fatigue, negative affect, physical function, and social function demonstrated clinical validity across a range of chronic conditions. *J Clin Epidemiol* 2016;73:89–102
 - 45 Novak CB, Mackinnon SE. Evaluation of nerve injury and nerve compression in the upper quadrant. *J Hand Ther* 2005;18(02):230–240
 - 46 Wilgis EFS. Techniques for diagnosis of peripheral nerve loss. *Clin Orthop Relat Res* 1982;x(163):8–14
 - 47 Wilton JP. Lower extremity focused neurologic examination. *Clin Podiatr Med Surg* 2016;33(02):191–202
 - 48 Shimokata H, Kuzuya F. Two-point discrimination test of the skin as an index of sensory aging. *Gerontology* 1995;41(05):267–272
 - 49 Bell-Krotoski J, Weinstein S, Weinstein C. Testing sensibility, including touch-pressure, two-point discrimination, point localization, and vibration. *J Hand Ther* 1993;6(02):114–123
 - 50 Hermann RP, Novak CB, Mackinnon SE. Establishing normal values of moving two-point discrimination in children and adolescents. *Dev Med Child Neurol* 1996;38(03):255–261
 - 51 Amirjani N, Ashworth NL, Gordon T, Edwards DC, Chan KM. Normative values and the effects of age, gender, and handedness on the Moberg Pick-Up Test. *Muscle Nerve* 2007;35(06):788–792
 - 52 Martina ISJ, van Koningsveld R, Schmitz PIM, van der Meché FGA, van Doorn PA. Measuring vibration threshold with a graduated tuning fork in normal aging and in patients with polyneuropathy. *European Inflammatory Neuropathy Cause and Treatment (INCAT) group. J Neurol Neurosurg Psychiatry* 1998;65(05):743–747
 - 53 Claus D, Carvalho VP, Neundörfer B, Blaise JF. Perception of vibration. Normal findings and methodologic aspects [in German]. *Nervenarzt* 1988;59(03):138–142
 - 54 Sun HH, Oswald TM, Sachanandani NS, Borschel GH. The “Ten Test”: application and limitations in assessing sensory function in the paediatric hand. *J Plast Reconstr Aesthet Surg* 2010;63(11):1849–1852
 - 55 Valdes K. Clinical relevance commentary in response to: the sensory function of the uninjured nerve in patients after median and ulnar nerve injury. *J Hand Ther* 2017;30(01):104–105
 - 56 Tong J, Mao O, Goldreich D. Two-point orientation discrimination versus the traditional two-point test for tactile spatial acuity assessment. *Front Hum Neurosci* 2013;7:579

- 57 Shooter D. Use of two-point discrimination as a nerve repair assessment tool: preliminary report. *ANZ J Surg* 2005;75(10):866–868
- 58 Hsu HY, Kuo LC, Kuan TS, et al. Determining the functional sensibility of the hand in patients with peripheral nerve repair: Feasibility of using a novel manual tactile test for monitoring the progression of nerve regeneration. *J Hand Ther* 2017;30(01):65–73
- 59 Ho ES. Evaluation of pediatric upper extremity peripheral nerve injuries. *J Hand Ther* 2015;28(02):135–142
- 60 Lundborg G, Rosén B. The two-point discrimination test—time for a re-appraisal? *J Hand Surg [Br]* 2004;29(05):418–422
- 61 Boldt R, Gogulski J, Gúzman-Lopéz J, Carlson S, Pertovaara A. Two-point tactile discrimination ability is influenced by temporal features of stimulation. *Exp Brain Res* 2014;232(07):2179–2185
- 62 Deslivia MF, Lee H-J, Adikrishna A, Jeon I-H. Decellularized nerves for upper limb nerve reconstruction: a systematic review of functional outcomes. *J Reconstr Microsurg* 2015;31(09):660–667
- 63 Rosén B, Lundborg G. A new tactile gnosis instrument in sensibility testing. *J Hand Ther* 1998;11(04):251–257
- 64 Bell-Krotoski JA, Buford WL Jr. The force/time relationship of clinically used sensory testing instruments. *J Hand Ther* 1997;10(04):297–309
- 65 Fess EE. Human performance: an appropriate measure of instrument reliability? *J Hand Ther* 1997;10(01):46–47
- 66 Moberg E. The unsolved problem—how to test the functional value of hand sensibility. *J Hand Ther* 1991;4(03):105–110
- 67 Marlowe ES, Bonner FJ Jr., Berkowitz AR. Correlation between two-point discrimination and median nerve sensory response. *Muscle Nerve* 1999;22(09):1196–1200
- 68 Jerosch-Herold C. A study of the relative responsiveness of five sensibility tests for assessment of recovery after median nerve injury and repair. *J Hand Surg [Br]* 2003;28(03):255–260
- 69 Zhang Z, Tannan V, Holden JK, Dennis RG, Tommerdahl M. A quantitative method for determining spatial discriminative capacity. *Biomed Eng Online* 2008;7:12
- 70 Dellon AL, Mackinnon SE, Crosby PM. Reliability of two-point discrimination measurements. *J Hand Surg Am* 1987;12(5, pt. 1):693–696
- 71 Novak CB, Mackinnon SE, Williams JI, Kelly L. Establishment of reliability in the evaluation of hand sensibility. *Plast Reconstr Surg* 1993;92(02):311–322
- 72 Bruns P, Camargo CJ, Campanella H, Esteve J, Dinse HR, Röder B. Tactile acuity charts: a reliable measure of spatial acuity. *PLoS One* 2014;9(02):e87384
- 73 Rosén B. Recovery of sensory and motor function after nerve repair. A rationale for evaluation. *J Hand Ther* 1996;9(04):315–327
- 74 Ceynowa M, Mazurek T, Pankowski R, Ročlawski M, Treder M. The thermal sensitivity test in evaluating outcome after peripheral nerve injury. *BioMed Res Int* 2015;2015:528356
- 75 MacDermid JC, Doherty T. Clinical and electrodiagnostic testing of carpal tunnel syndrome: a narrative review. *J Orthop Sports Phys Ther* 2004;34(10):565–588
- 76 Patel MR, Bassini L. A comparison of five tests for determining hand sensibility. *J Reconstr Microsurg* 1999;15(07):523–526
- 77 Strauch B, Lang A. The ten test revisited. *Plast Reconstr Surg* 2003;112(02):593–594
- 78 Moberg E. Objective methods for determining the functional value of sensibility in the hand. *J Bone Joint Surg Br* 1958;40-B(03):454–476
- 79 Omer GE Jr. Sensation and sensibility in the upper extremity. *Clin Orthop Relat Res* 1974;(104):30–36
- 80 Dellon AL. Clinical use of vibratory stimuli to evaluate peripheral nerve injury and compression neuropathy. *Plast Reconstr Surg* 1980;65(04):466–476
- 81 Bear-Lehman J, Abreu BC. Evaluating the hand: issues in reliability and validity. *Phys Ther* 1989;69(12):1025–1033
- 82 Novak CB, Mackinnon SE, Kelly L. Correlation of two-point discrimination and hand function following median nerve injury. *Ann Plast Surg* 1993;31(06):495–498
- 83 Lundborg G, Dahlin LB, Lundström R, Necking LE, Strömberg T. Vibrotactile function of the hand in compression and vibration-induced neuropathy. Sensibility index—a new measure. *Scand J Plast Reconstr Surg Hand Surg* 1992;26(03):275–279
- 84 Strauch B, Lang A, Ferder M, Keyes-Ford M, Freeman K, Newstein D. The ten test. *Plast Reconstr Surg* 1997;99(04):1074–1078
- 85 Uddin Z, MacDermid J, Packham T. The ten test for sensation. *J Physiother* 2013;59(02):132
- 86 Jerosch-Herold C. Assessment of sensibility after nerve injury and repair: a systematic review of evidence for validity, reliability and responsiveness of tests. *J Hand Surg [Br]* 2005;30(03):252–264
- 87 Fonseca MCR, Elui VMC, Lalone E, et al. Functional, motor, and sensory assessment instruments upon nerve repair in adult hands: systematic review of psychometric properties. *Syst Rev* 2018;7(01):175
- 88 Hsu H-Y, Kuo L-C, Jou IM, Chen S-M, Chiu H-Y, Su F-C. Establishment of a proper manual tactile test for hands with sensory deficits. *Arch Phys Med Rehabil* 2013;94(03):451–458
- 89 Guy RJ, Clark CA, Malcolm PN, Watkins PJ. Evaluation of thermal and vibration sensation in diabetic neuropathy. *Diabetologia* 1985;28(03):131–137
- 90 Ingram LA, Butler AA, Walsh LD, Brodie MA, Lord SR, Gandevia SC. The upper limb physiological profile assessment: description, reliability, normative values and criterion validity. *PLoS One* 2019;14(06):e0218553