# Evidence and Techniques in Rehabilitation Following Nerve Injuries

Christine B. Novak, PT, PhD[a,b,*],
Rebecca L. von der Heyde, PhD, OTR/L, CHT[c]

**KEYWORDS**

• Rehabilitation • Hand therapy • Treatment

**KEY POINTS**

- Rehabilitation is essential to optimize sensorimotor function and outcome following nerve injury.
- The strategies in early phase rehabilitation are related to pain and edema control, range of motion and neural mobility.
- Alterations in cortical mapping with nerve injury/recovery and sensory and motor reeducation support the importance of rehabilitation following nerve injury.

Injury to a peripheral nerve causes alterations in both the peripheral and central nervous system, and these changes begin immediately after injury and continue through recovery. These changes can result in substantial loss of motor and sensory function with high levels of impairment and a negative impact on health-related quality of life.[1,2] Following upper extremity peripheral nerve injury and surgery, rehabilitation is essential to optimize sensorimotor function and outcome. This review presents the evidence and related literature regarding a few key topics related to rehabilitation following peripheral nerve injury and surgery. In general, the level of evidence in the published literature is limited and comprises predominately low-level evidence.

## GENERAL PRINCIPLES

In the early period following surgery, the main goals are related to range of motion, pain, and edema control. Patient education is important and begins preoperatively to ensure that patients understand nerve injury and recovery, the surgical procedure, and postoperative course.

The initial strategies following surgery include decreasing postoperative edema and pain management. Neuropathic pain has been associated with poor outcome and high levels of disability.[2–4] In cases of severe neuropathic pain, a multidisciplinary team approach may be necessary with referral to a pain management program. Immobilization following surgery is used to protect the nerve coaptation site. Initially, a bulky dressing is applied; in the authors' practice, this dressing is removed 2 to 3 days after surgery. Immobilization, such as a splint, sling, or shoulder immobilizer, is continued to protect the nerve coaptation site. Range of motion of the proximal and distal joints is encouraged to promote neural gliding. Similar to improved outcomes with tendon gliding and controlled motion following flexor tendon repair, the emphasis on controlled motion following nerve reconstruction has allowed the authors to incorporate early motion to decrease adhesions and promote neural gliding.

[a] Department of Surgery, University of Toronto, 399 Bathurst Street, EW2-422, Toronto, Ontario, M5T 2S8, Canada; [b] Toronto Rehab and Hand Program, University Health Network, 399 Bathurst Street, EW2-422, Toronto, Ontario, M5T 2S8, Canada; [c] Occupational Therapy Department, Concordia University Wisconsin, 12800 N Lake Shore Drive, Mequon, WI 53097, USA
* Corresponding author. TWH Hand Centre, 399 Bathurst Street, EW2-422, Toronto, Ontario M5T 2S8, Canada.
*E-mail address:* Christine.novak@uhn.ca

Hand Clin 29 (2013) 383–392
http://dx.doi.org/10.1016/j.hcl.2013.04.012

In the literature, there are varying reports on the recommended period of immobilization following nerve repair or graft and vary between a few days to several weeks. In part, this variability depends on the tension applied to the repair site with range of motion, patient factors, and surgeon preference.[5–10] Early postoperative range of motion is advocated with the hypothesis that this motion will minimize scarring and encourage neural mobility. Longer periods of immobilization are based on the hypothesis that early range of motion will increase scar and collagen formation at the nerve coaptation site and, thus, impede nerve regeneration.[5–9,11–15] The ideal period of time for immobilization to balance protection of the nerve coaptation site and to promote neural mobility remains to be established. For repair sites that may undergo tension with movement, such as with a direct end-to-end repair, this period may be as long as 3 weeks, particularly if the joint range of motion induces increased tension on the nerve. For nerve graft or transfer whereby no tension is transferred to the coaptation site with movement, the time of immobilization or protected motion may be shortened to 3 to 10 days following surgery, although some surgeons continue restriction of movement for 3 weeks.

The period of immobilization is also dependent on the surrounding soft tissues, which may have been repaired during the surgical procedure. In cases of brachial plexus reconstruction whereby the pectoralis major is detached and reattached, a 4-week period of immobilization in adduction and internal rotation of the shoulder is recommended. Range of motion of the proximal and distal joints that is not included in the immobilization will promote neural mobility and gliding and assist in both pain and edema control. Following immobilization, range-of-motion exercises should continue until full range of motion is achieved. As muscle reinnervation occurs, patients should be reevaluated frequently to ensure full range of motion is maintained and monitored for muscle reinnervation. Muscle imbalance may be persistent until sufficient strength is attained and normal movement patterns can be performed.

## MOTOR NERVE TRANSFER

Nerve transfers present the unique situation whereby a muscle is innervated by a new proximal nerve source, thus, altering the previously established cortical map and motor patterns. Therefore, rehabilitation strategies following nerve transfer must be directed to the sensorimotor systems via increased emphasis on cortical remapping and movement patterns, in addition to increased muscle strength and muscle balance. Motor nerve transfers have been more commonly used as a salvage procedure when nerve repair or graft was not possible, such as an intercostal to musculocutaneous nerve transfer in brachial plexus avulsion injuries.[16–18] Although reinnervation of the biceps muscle was successful with adequate elbow flexion, the overall patient outcome was less than optimal because of the devastating nature of the injury and no recovery of hand function. More recently, the use of nerve transfers has expanded to include more distal nerve injury as well as spinal cord injury; outcomes with these nerve transfers have been encouraging.[10,19–24]

Numerous clinical studies have reported outcomes following nerve transfer, including patients with nerve injuries to the brachial plexus, median, ulnar, and radial nerves.[10,19–24] Comparison between surgical procedures and studies is challenging because of the wide variety of preoperative and postoperative outcome assessments, including patient self-report and surgeon or therapist assessment. Garg and colleagues[25] performed a systematic literature review to evaluate the outcomes following nerve transfer or nerve graft in patients with upper brachial plexus injuries. Using the British Medical Research Council (MRC) muscle grading system, the investigators report improved outcomes in shoulder and elbow function following nerve transfer. However, it is important to recognize that not all studies use the MRC scale uniformly.

In the authors' literature review, they did not find any studies that specifically evaluated the efficacy of rehabilitation following nerve transfers. In most outcome studies, the nerve transfer surgical technique and postoperative rehabilitation are described in the methodology and outcomes are reported for the procedure, including postoperative management. The authors' treatment of patients with motor nerve transfer includes preoperative education and postoperatively early and late-phase rehabilitation.

With evidence of muscle reinnervation, rehabilitation is focused on sensorimotor reeducation and restoration of muscle balance. Because a new donor nerve is transferred to the recipient nerve to target muscle reinnervation, the motor patterns and cortical mapping are altered. Initially, contraction of the reinnervated muscle will require contraction of the donor muscle; with the establishment of new motor patterns and cortical remapping, the action will be performed without the donor muscle. As with any new task, practice and repetition with appropriate feedback is necessary to achieve success and correct motor patterns.[26]

## DIGITAL NERVE REPAIR

The literature pertaining to rehabilitation following nerve repair attends primarily to the major peripheral nerves of the upper extremity, offering evidence for both conservative and postoperative management of median, radial, and ulnar injuries. A dearth of information regarding therapeutic interventions and expectations following digital nerve repair is noted despite progress in surgical techniques. Therefore, this section reviews the current literature on digital nerve repair as a means to direct therapeutic decision making and offer evidence-based benchmarks for clinical outcomes.

### *Recovery Based on Surgical Procedure*

From a rehabilitative perspective, knowledge of the type of repair or reconstruction offers the therapist insight to potential outcomes, including time frames for sensory recovery. Repair following digital nerve injury is typically accomplished using one of 4 techniques: end-to-end neurorrhaphy, nerve grafts, nerve conduits, or end-to-side neurorrhaphy.[27] Lohmeyer and colleagues[28] reported that direct repair is used in approximately 82% of cases, whereas the use of a graft or conduit is optimal about 18% of the time.

Studies have used a combination of subjective and objective measures as a means to assess outcomes following digital nerve repair. Most common are static/moving 2-point discrimination and pain.[29] Static 2-point discrimination is reported both in millimeters and using the modified guidelines of the American Society for Surgery of the Hand.[29] Less often, researchers have included sensory threshold testing; range of motion; and more recently, self-report measures, such as the Disabilities of the Arm, Shoulder, and Hand (DASH), the Michigan Hand Outcomes Questionnaire (MHQ), and the Cold Intolerance Severity Score (CISS).[2–4,30–42]

Examples of sensory recovery as reported in static 2-point discrimination can be gleaned from current research.[28,43–47] These studies include current approaches of nerve conduit and grafting techniques with follow-up measurement ranging from 6 months to 4 years. Of particular note are the favorable outcomes of decellularized nerve allografts at the 9-month time frame with static 2-point discrimination of 5.5 mm.[46] More typically, at 1 year after surgery, patients with conduits and vein grafts were noted to have results at or near 7 mm.[28,43,47] Wang and colleagues[48] evaluated 74 patients following primary digital nerve repair (at least 1 year after surgery) for comparison, and 49% of patients had static 2-point discrimination of 7 mm or less. A recent systematic review including 14 articles with data for 191 nerves found no statistically significant difference in outcomes between differing digital nerve repair techniques.[27] This review included a mean follow-up of 28 months and reported only 25% of patients having excellent results (<6 mm).

Variables that have been associated with outcomes following digital nerve repair include age, length of follow-up after surgery, delay in repair from time of the initial injury, type of trauma, and gap length. Of these variables, younger age has been established as a significant predictor of recovery after digital nerve repair by multiple investigators.[27,48,49] Weinzweig and colleagues[49] also identified mechanism of injury as a variable of significance, whereas Rinker and Liau[44] reported that smokers and patients with workers' compensation demonstrated worse sensory recovery at 12 months. These studies from the surgical literature provide data for comparison of patient outcomes over time.

### *Immobilization Following Repair*

Historically, patients with a digital nerve repair have been treated with immobilization of the proximal interphalangeal (PIP) joint at 30° of flexion for 3 weeks following surgery. Although some surgeons have progressed from this conservative approach, the strategy of blocking the PIP joint to avoid deleterious tension at the repair site remains in practice. The primary concern in using this approach is the likelihood of persistent flexion contractures at the PIP joint that require additional time and interventions to resolve. The close-packed position of the PIP joint is full extension, affording maximal length of the connective tissue structures surrounding the joint, optimal articulation of the joint surfaces, and minimal excess space within the joint. Any positioning toward flexion at the PIP negatively impacts these variables, allowing volar plate compression and contraction of the checkrein ligaments.[50] Digital nerves repaired with tension in extension may require immobilization in a shortened position; however, the amount of flexion and progression of active extension should be pursued on a case-by-case basis.

Positioning of joints after digital nerve repair as discussed in the current, surgical literature is directed toward the metacarpophalangeal (MP) joint. In a cadaveric study that measured the tension produced during passive finger range of motion, there was no appreciable tension with PIP motion regardless of MP position within the normal range.[51] However, when the MP joint was passively moved into hyperextension, tension on the nerve was notably increased (~4N). The investigators recommended the use of orthotics to block the MP joint in flexion to avoid tension of the digital nerve. Chen and colleagues[43,45] also reported on this type of MP blocking orthotic.[43,45] Primarily intending to assess the outcomes of a dorsal digital nerve island flap and a proper digital nerve dorsal branch transfer, the investigators used a position of 70° MP flexion and 0° PIP and distal interphalangeal extension for immobilization following surgery.[43,45] The results of both studies yielded the return of sensibility commensurate with similar studies.

The combined injury of flexor tendons and digital nerves in zone II provides a typical case in which PIP flexion is used postsurgically. To address this specific diagnosis, Yu and colleagues[52] compared patients with primary, isolated digital nerve repairs to those with a concomitant flexor tendon repair. No significant differences were observed between groups in 2-point discrimination or sensory threshold despite the tendon/nerve group being mobilized using a Kleinert protocol starting at day 4 and the nerve group being immobilized for 21 days. The investigators concluded that immobilization of digital nerves for 3 weeks was unnecessary if tension on the healing nerve could be avoided. It is of note that the Kleinert protocol includes a dorsal blocking orthosis with MP flexion and interphalangeal extension as referenced in previous studies.[43,45,51]

## ELECTRICAL STIMULATION

As an adjunct to rehabilitation, a variety of modalities have been recommended for treatment following nerve injury and repair. A commonly used modality is electrical muscle stimulation; it has also been reported as electrical stimulation, neuromuscular electrical stimulation, functional electrical stimulation, and transcutaneous electrical stimulation. The parameters of the electrical stimulation vary with different types of applications, and there are different protocols described in the rehabilitation literature.[53] For stimulation of denervated muscle, a direct current or galvanic stimulation is used; for innervated muscle, an indirect current may be used. In general, the level of evidence in clinical studies for electrical stimulation of denervated muscle is limited and largely based on small series reports.

Following injury to a motor nerve, a cascade of events occurs resulting in muscle denervation with both structural and functional changes to the muscle.[54] Short-term denervation atrophy is reversible and does not result in long-term deficits. However, long-term denervation atrophy results in irreversible pathologic changes to the muscle. Following denervation, the optimal outcome occurs when motor axons are promptly supplied to denervated muscle, thus, providing rapid reinnervation. Longer durations of denervation are associated with poorer outcomes. However, the definitive timeline to muscle reinnervation before irreversible changes remains undefined but is likely in the period of 18 to 24 months; muscle reinnervation is possible for longer periods following injury with incontinuity nerve lesions compared with transection injuries. Overall, the evidence in the literature supports the assertion that the best recovery of muscle function occurs with shorter durations of muscle denervation.

The treatment goals remain focused on providing innervation to the denervated muscle before irreversible muscle changes associated with denervation. Rehabilitation strategies for the treatment of denervated muscle have included electrical stimulation with the goal of prolonging the time before muscle degeneration by providing an external source of stimulation to the muscle fibers. Studies of both innervated and denervated muscle have shown benefits to the contractile properties of the muscle with increased contractile activity, which may be induced through electrical stimulation.[55] However, in cases of denervated muscle, the efficacy of electrical stimulation to prolong the time period before irreversible muscle atrophy and increase the capacity for reinnervation remains unanswered. In a rat sciatic nerve model, improved functional recovery was reported for low-intensity stimulation.[56] However, at higher intensities (2 Hz), adverse effects (impaired functional recovery) of electrical stimulation were reported.[56] Although these adverse effects may not be directly transferred to humans, it does raise the question of the benefit versus detrimental effects that may be attributed to electrical stimulation. There are many clinical reports using electrical stimulation following motor nerve injury, and there are a limited number of published clinical studies that have provided very low levels of evidence. Many of the studies using nerve injury animal models used direct electrical stimulation with implanted intramuscular wires, and some studies used implanted stimulators. Typically in clinical practice, a direct current using galvanic stimulation is applied via surface electrodes. The authors' literature review did not reveal any efficacy trials in humans to support the use of direct current electrical stimulation with external electrodes and improvement of outcomes in denervated muscle, specifically to prolong the time for muscle innervation. Given the lack of strong clinical evidence and the variation of the technique to apply the electrical stimulation in the clinical setting of patients with nerve injury, the authors do not advocate the use of galvanic stimulation in denervated muscle.

Electrical stimulation following motor nerve injury is typically applied directly to the muscle with the goal of modifying the muscle fibers. Other approaches to optimize muscle recovery have been directed toward enhancing nerve regeneration and decreasing the duration of denervation. These strategies have included the use of electrical stimulation, nerve growth factors, conditioning lesions, and immunosuppressive drugs. The electrical stimulation used in this type of application is targeted to the nerve with the goal of accelerating nerve regeneration and, thus, providing more timely muscle reinnervation and decreasing the time of muscle denervation. Studies investigating 1 hour of electrical stimulation in rodent and rabbit models have shown beneficial effects with accelerated reinnervation and functional recovery.[57,58] In a clinical study, Gordon and colleagues[59] investigated patients with carpal tunnel syndrome who were treated for 1 hour with electrical stimulation of the median nerve immediately after carpal tunnel release. Postoperative low frequency electrical stimulation of the nerve was associated with accelerated axonal regeneration and improved motor and sensory parameters. These studies provide proof of principle for the use of low-frequency electrical stimulation and accelerated nerve regeneration.

Electrical stimulation of innervated muscle may provide increased strength, which is necessary for function; but muscle strength is only one component of upper extremity motor function. The establishment of good motor function following nerve injury also requires the restoration of full passive joint range of motion, muscle balance, and normal motor patterns. During the period of time from nerve injury to reinnervation, many patients develop altered compensatory movement patterns, muscle weakness from disuse rather than denervation, and altered sensorimotor cortical mapping. Integration and coordination of motor and sensory reeducation are necessary to optimize outcome.

## SENSORY REEDUCATION

Following nerve injury, in addition to the peripheral changes that occur at the muscle and sensory end-organ level, there are rapid changes that occur in the cortex. Injury to a sensory nerve will result in decreased sensory input to the cortex and reorganization of the somatosensory cortical map.[60–63] Rehabilitation treatments have been focused on strategies to alter the detrimental effects of deafferentation. Following several clinical reports in the literature in the 1970s,[29,64–66] sensory reeducation has been routinely used after peripheral nerve injury to optimize outcomes. Numerous clinical studies have reported outcomes after median, ulnar, and digital nerve injuries and repair with descriptions of postoperative sensory reeducation.[64,66–69] Recent reviews have evaluated the literature related to outcomes following sensory reeducation in patients with upper extremity nerve repair.[70,71] In general, there is evidence to support the use of sensory reeducation following peripheral nerve injury and repair. However, the limitations of the studies reviewed included the use of a variety of reported outcome measures and the lack of detailed descriptions for the sensory reeducation programs used.

Sensory reeducation is used to improve sensibility and also to decrease pain, allodynia, and hyperalgesia. A variety of techniques have been described, including varying textures, localization and discrimination, and mobility tasks. As sensibility improves, the strategies are increased to challenge the sensory system and optimize cortical remapping and normal movement patterns.

Sensory reeducation programs typically begin with evidence of sensory end-organ reinnervation. Early phase reeducation programs before reinnervation have been described to enhance the sensory cortex remapping.[69,72–74] These techniques have included mirror imagery, temporary anesthesia, and audio-tactile and visuo-tactile training.

## SELF-REPORT OUTCOMES ASSESSMENT

The use of outcome measures to assess and demonstrate patient progress has recently changed from a preference to an expectation. A myriad of patient self-report outcome measures are available for use by the hand surgeon and therapist ranging from general to regional to disease-specific. The following section aims to summarize both well-established and more novel tools that are being used to evaluate outcomes in patients with peripheral nerve injuries.

### *DASH*

The most widely used regional, upper extremity self-report outcome measure for disability, the DASH, was designed to allow comparison of conditions throughout the upper extremity while considering it a single functional unit.[34] Two concepts of symptoms and functional status compose the 30-item tool and are assessed from 1 (no difficulty, symptoms, or limitations) to 5 (unable to complete activities and extreme symptoms and signs). Scores range from 0 to 100, with higher scores indicating increased perceived disability. Continued testing by the original investigators yielded a suggested minimal detectable change (MDC) score of 12.75, with a suggested mean MDC of 13 (range 8–17) published on the DASH website (http://www.dash.iwh.on.ca/faq).[30]

Specific to nerve injuries, the DASH has been suggested as a responsive tool for use with patients following carpal tunnel release.[33,36] Commonly used in clinical research, this tool has also been used to identify predictors of disability in patients with peripheral nerve injuries. Studies by Novak and colleagues[1,2] found significantly higher perceived disability in patients with brachial plexus injuries, with mean DASH scores ranging from 44 to 52. The nerve injured, pain, and older age were distinguished as predictors of higher DASH scores in addition to work status, time since injury, cold sensitivity, and pain catastrophizing.[1,2]

### *MHQ*

The MHQ consists of 67 questions that address domains of overall hand function, physical function with activities of daily living tasks, esthetics, and satisfaction with hand function.[40] Questions are formatted in Likert scales ranging from 1 to 5; summed and averaged scores are normalized from 0 to 100. The MHQ is defined as hand specific; it addresses the function of each upper extremity as a means of analyzing independent use, hand dominance, and bilateral involvement.[39]

Relative to peripheral nerve outcomes, the MHQ has been found to be sensitive to clinical change for patients with carpal tunnel syndrome and after carpal tunnel release.[36,42,75] Minimally clinically important differences have been published specifically for patients with carpal tunnel syndrome as pain, 23; function, 13; and work, 8.[76] In addition, this tool was suggested to have a higher overall responsiveness as compared with the DASH and Patient-Specific Functional Scale (PSFS) in a sample of 81 patients with carpal tunnel, wrist pain, and finger contractures.[36] The Brief MHQ was recently introduced to complete when a shorter time is desirable.[77]

### *Disease-Specific Measure: the Boston Questionnaire for Carpal Tunnel Syndrome*

The Boston Questionnaire was developed as a disease-specific measure for clients with carpal tunnel syndrome, including an 11-item Symptom Severity Scale and an 8-item Functional Status Scale.[78] Items are evaluated for a typical day in the past 2 weeks and answered on a Likert scale. A score of 1 indicates a low level of symptom/difficulty, whereas a score of 5 indicates that patients are highly symptomatic or unable to complete functional tasks. The answers are averaged, with higher scores indicating decreased status. The Boston Questionnaire has been shown to be reliable, valid, and sensitive to change in clients with carpal tunnel syndrome[78–83] and more sensitive to clinical change than generic[33,75,79,84] and regional measures.[75] Disease-specific self-report measures allow inclusion of specific items related to the condition or diagnosis of interest.

### *CISS*

The CISS is a 6-item questionnaire developed to assess the impact of cold intolerance on daily function.[35] Using Likert scales, patients are asked to determine cold-induced symptom type, incidence, relief, and prevention. In addition, 2 questions regarding functional tasks that provoke symptoms and those that are limited because of symptoms are included in the tool. The total score ranges from 0 to 100, with higher scores indicating greater cold intolerance. The CISS has been reported as reliable and valid for patients with upper extremity injuries.[31,32,35,38,85] Specific to nerve injury, a study of 61 patients with brachial plexus injuries yielded a mean CISS score of 34 that was significantly higher in women.[86] Pain ratings, perceived disability, and time since injury were identified as predictors of cold intolerance in the study.

### *PSFS*

The PSFS is a self-report measure that asks patients to independently identify specific activities that they have difficulty with or are unable to perform.[87] The tool incorporates 10-cm visual analog scales that are anchored based on the perceived ability for up to 5 separate activities. The PSFS was confirmed to have construct and concurrent validity, good reliability, and responsiveness for patients with upper extremity musculoskeletal problems.[36,88] A minimal detectable change of 3 with a minimally important difference of 1.2 was reported. Specific to nerve injury, the PSFS was found to be sensitive to change for patients with carpal tunnel syndrome up to 6 months after surgery, and construct validity was confirmed in a sample of 157 patients with upper extremity nerve injury.[36,89] Patients in the latter study had a mean PSFS score of 3.1; significantly lower scores were reported in those with brachial plexus injuries. The PSFS provides the opportunity for patients to select items that are specifically relevant. However, comparison between patients is more challenging because of the variation in activities selected. The use of more generic questionnaires, such as the

DASH and MHQ, in combination with the PSFS may provide a more comprehensive evaluation.

## SUMMARY

The strategies used in rehabilitation following peripheral nerve injury and reconstruction is supported in basic science and small cohort clinical studies. Although strong evidence with randomized controlled clinical trials is lacking, the strategies related to early mobilization, altered cortical mapping and remapping, and sensory and motor reeducation support the importance of rehabilitation following nerve injury. Future studies using valid, reliable outcome measures (quantitative, qualitative, and self-reported) will provide additional direct evidence for the use of postoperative rehabilitation to optimize recovery and minimize disability.

## REFERENCES

1. Novak CB, Anastakis DJ, Beaton DE, et al. Patient reported outcome following peripheral nerve injury. J Hand Surg Am 2009;34:281–7.
2. Novak CB, Anastakis DJ, Beaton DE, et al. Biomedical and psychosocial factors associated with disability after peripheral nerve injury. J Bone Joint Surg Am 2011;93:929–36.
3. Jensen MP, Chodroff MJ, Dworkin RH. The impact of neuropathic pain on health-related quality of life: review and implications. Neurology 2007;68: 1178–82.
4. Novak CB, Katz J. Neuropathic pain in patients with upper extremity nerve injury. Physiother Can 2010;62:190–201.
5. Birch R. Nerve repair. In: Wolfe SW, Hotchkiss RN, Pederson WC, et al, editors. Green's operative hand surgery. Philadelphia: Elsevier Churchill Livingstone; 2011. p. 1035–74.
6. Boyd KU, Fox IK, Mackinnon SE. Nerve transfers. In: Neligan PC, Chang J, editors. Plastic surgery hand and upper extremity. London: Elsevier Saunders; 2013. p. 719–44.
7. Farnedo S, Thorfinn J, Dahlin LB. Peripheral nerve injuries of the upper extremity. In: Neligan PC, Chang J, editors. Plastic surgery hand and upper extremity. London: Elsevier Saunders; 2013. p. 694–718.
8. Lundborg G. Nerve injury and repair. Philadelphia: Elsevier Churchill Livingstone; 2005.
9. Mackinnon SE, Dellon AL. Surgery of the peripheral nerve. New York: Thieme Medical Publishers; 1988.
10. Mackinnon SE, Novak CB. Nerve transfers. Hand Clin 1999;15:643–66.
11. Millesi H. Factors affecting the outcome of peripheral nerve surgery. Microsurgery 2006;26: 295–302.
12. Lee WP, Constantinescu MA, Butler PE. Effect of early mobilization on healing of nerve repair: histologic observations in a canine model. Plast Reconstr Surg 1999;104:1718–25.
13. Millesi H, Zoch G, Rath T. The gliding apparatus of peripheral nerve and its clinical significance. Ann Hand Surg 1990;9:87–97.
14. Millesi H, Zoch G, Reihsner R. Mechanical properties of peripheral nerves. Clin Orthop Relat Res 1995;314:76–83.
15. Schmidhammer R, ZZandieh S, Hopf R, et al. Alleviated tension at the repair site enhances functional regeneration: the effect of full range of motion mobilization on the regeneration of peripheral nerves - histologic, electrophysiologic and functional results in a rat model. J Trauma 2004;56: 571–84.
16. Chuang DC, Yeh MC, Wei FC. Intercostal nerve transfer of the musculocutaneous nerve in avulsed brachial plexus injuries: evaluation of 66 patients. J Hand Surg Am 1992;17:822–8.
17. Chuang DC, Epstein MD, Yeh MC, et al. Functional restoration of elbow flexion in brachial plexus injuries: results in 167 patients. J Hand Surg 1993; 18:285–91.
18. Waikakul S, Wongtragul S, Vanadurongwan V. Restoration of elbow flexion in avulsion brachial plexus injury: comparing spinal accessory intercostal nerve neurotization. J Hand Surg 1999;24: 571–7.
19. Lurje A. Concerning surgical treatment of traumatic injury of the upper division of the brachial plexus (Erb's type). Ann Surg 1948;127:317–26.
20. Mackinnon SE, Novak CB, Myckatyn TM, et al. Results of reinnervation of the biceps and brachialis muscles with a double fascicular transfer. J Hand Surg Am 2005;30:978–85.
21. Novak CB, Mackinnon SE. A distal anterior interosseous nerve transfer to the deep motor branch of the ulnar nerve for reconstruction of high ulnar nerve injuries. J Reconstr Microsurg 2002;18: 459–63.
22. Novak CB, Tung TH, Mackinnon SE. Patient outcome following a thoracodorsal to musculocutaneous nerve transfer for reconstruction of elbow flexion. Br J Plast Surg 2003;55:416–9.
23. Oberlin C, Beal D, Leechavengvongs S, et al. Nerve transfer to biceps muscle using a part of ulnar nerve for C5-C6 avulsion of the brachial plexus: anatomical study and report of four cases. J Hand Surg Am 1994;19:232–7.
24. Tung TH, Novak CB, Mackinnon SE. Nerve transfers to the biceps and brachialis branches to improve elbow flexion strength after brachial plexus injuries. J Neurosurg 2003;98:313–8.
25. Garg R, Merrell GA, Hillstrom HJ, et al. Comparison of nerve transfers and nerve grafting for

traumatic upper plexus palsy: a systematic review and analysis. J Bone Joint Surg Am 2011; 93:819–29.
26. Duff SV. Impact of peripheral nerve injury on sensorimotor control. J Hand Ther 2005;18:277–91.
27. Mermans JF, Franssen BB, Serroyen J, et al. Digital nerve injuries: a review of predictors of sensory recovery after microsurgical digital nerve repair. Hand 2012;7:233–41.
28. Lohmeyer JA, Siemers F, Machens HG, et al. The clinical use of artificial nerve conduits for digital nerve repair: a prospective cohort study and literature review. J Reconstr Microsurg 2009;25:55–61.
29. Dellon AL, Kallman CH. Evaluation of functional sensation in the hand. J Hand Surg Am 1983;8: 865–70.
30. Beaton DE, Katz JN, Fossel AH, et al. Measuring the whole or the parts? Validity, reliability and responsiveness of the Disabilities of the Arm, Shoulder and Hand outcome measure in different regions of the upper extremity. J Hand Ther 2001; 14:128–46.
31. Carlsson I, Cederlund R, Hoglund P, et al. Hand injuries and cold sensitivity: reliability and validity of cold sensitivity questionnaires. Disabil Rehabil 2008;30:1920–8.
32. Carlsson I, Rosen B, Dahlin LB. Self-reported cold sensitivity in normal subjects and in patients with traumatic hand injuries or hand-arm vibration syndrome. BMC Musculoskelet Disord 2010;11: 89–99.
33. Gay RE, Amadio PC, Johnson JC. Comparative responsiveness of the Disabilities of the Arm, Shoulder and Hand, the Carpal Tunnel Questionnaire, and the SF-36 to clinical change after carpal tunnel release. J Hand Surg Am 2003;28:250–4.
34. Hudak PL, Amadio PC, Bombardier C. Development of an upper extremity outcome measure: the DASH (Disabilities of the Arm, Shoulder and Hand). Am J Ind Med 1996;29:602–8.
35. Irwin MS, Gilbert SE, Terenghi G, et al. Cold intolerance following peripheral nerve injury. Natural history and factors predicting severity of symptoms. J Hand Surg Am 1997;22:308–16.
36. McMillan CR, Binhammer PA. Which outcome measure is the best? Evaluating responsiveness of the Disabilities of the Arm, Shoulder and Hand questionnaire, the Michigan Hand Questionnaire and the Patient-Specific Functional Scale following hand and wrist surgery. Hand 2009;4:311–8.
37. Ruijs AC, Jaquet JB, Kalmijn S, et al. Median and ulnar nerve injuries: a meta-analysis of predictors of motor and sensory recovery after modern microsurgical nerve repair. Plast Reconstr Surg 2005; 116:484–94.
38. Ruijs AC, Jaquet JB, Daanen HA, et al. Cold intolerance of the hand measured by the CISS questionnaire in the normative study population. J Hand Surg Am 2006;31:533–6.
39. Amadio PC. Outcome assessment in hand surgery and hand therapy: an update. J Hand Ther 2001; 14:63–8.
40. Chung KC, Pillsbury MS, Walters MR, et al. Reliability and validity testing of the Michigan Hand Outcomes Questionnaire. J Hand Surg Am 1998; 23:575–87.
41. Chung KC, Hamill JB, Walters MR, et al. The Michigan Hand Outcomes Questionnaire (MHQ): assessment of responsiveness to clinical change. Ann Plast Surg 1999;42:619–22.
42. Kotsis SV, Chung KC, Arbor A. Responsiveness of the Michigan Hand Outcomes Questionnaire and the Disabilities of the Arm, Shoulder and Hand Questionnaire in carpal tunnel surgery. J Hand Surg Am 2005;30:81–6.
43. Chen C, Zhang X, Shao X, et al. Treatment of a combination of volar soft tissue and proper digital nerve defects using the dorsal digital nerve island flap. J Hand Surg Am 2010;35:1655–62.
44. Rinker B, Liau JY. A prospective study comparing woven polyglycolic acid and autogenous vein conduits for reconstruction of digital nerve gaps. J Hand Surg Am 2011;36:775–8.
45. Chen C, Tang P, Zhang X. Finger sensory reconstruction with transfer of the proper digital nerve dorsal branch. J Hand Surg Am 2013;38: 82–9.
46. Karabekmez FE, Duymaz A, Moran SL. Early clinical outcomes with the use of decellularized nerve allograft for repair of sensory defects within the hand. Hand 2009;4:245–9.
47. Bushnell BD, McWilliams AD, Whitener GB, et al. Early clinical experience with collagen nerve tubes in digital nerve repair. J Hand Surg Am 2008;33: 1081–7.
48. Wang W, Crain GM, Baylis W, et al. Outcome of digital nerve injuries in adults. J Hand Surg Am 1996; 21:138–43.
49. Weinzweig N, Chin G, Mead M, et al. Recovery of sensibility after digital neurorraphy: a clinical investigation of prognostic factors. Ann Plast Surg 2000; 44:610–7.
50. Hammert WC. Hand fractures and joint injuries. In: Neligan PC, Chang J, editors. Plastic surgery: hand and upper extremity. St Louis (MO): Elsevier Saunders; 2013. p. 138–60.
51. Goldberg SH, Jobin CM, Hayes AG, et al. Biomechanics and histology of intact and repaired digital nerves: an in vitro study. J Hand Surg Am 2007;32: 474–82.
52. Yu RS, Catalano LW, Barron OA, et al. Limited, protected postsurgical motion does not affect the results of digital nerve repair. J Hand Surg Am 2004;29:302–6.

53. Michlovitz SL. Is there a role for ultrasound and electrical stimulation following injury to tendon and nerve? J Hand Ther 2005;18:292–6.
54. Lien SC, Cederna PS, Kuzon WM. Optimizing skeletal muscle reinnervation with nerve transfer. Hand Clin 2008;24:445–54.
55. Dow DE, Cederna PS, Hassett CA, et al. Number of contractions to maintain mass and force of a denervated rat muscle. Muscle Nerve 2004;30:77–86.
56. Lu MC, Tsai CC, Chen SC, et al. Use of electrical stimulation at different current levels to promote recovery after peripheral nerve injury in rats. J Trauma 2009;67:1066–72.
57. Ahlborn P, Schachner M, Irintchev A. One hour electrical stimulation accelerates functional recovery after femoral nerve repair. Exp Neurol 2007;208:137–44.
58. Gordon T, Chan KM, Sulaiman OA, et al. Accelerating axon growth to overcome limitations in functional recovery after peripheral nerve injury. Neurosurgery 2009;65:132–44.
59. Gordon T, Amirjani N, Edwards DC, et al. Brief post-surgical electrical stimulation accelerates axon regeneration and muscle reinnervation without affecting the functional measures in carpal tunnel syndrome patients. Exp Neurol 2010;223:192–202.
60. Merzenich MM, Harrington T. The sense of flutter-vibration evoked by stimulation of the hairy skin of primates: comparison of human sensory capacity with the responses of mechanoreceptive afferents innervating the hairy skin of monkeys. Exp Brain Res 1969;9:236–60.
61. Merzenich MM, Jenkins WM. Reorganization of cortical representations of the hand following alterations of skin inputs induced by nerve injury, skin island transfers and experience. J Hand Ther 1993;6:89–104.
62. Wall JT, Kaas JH, Sur M, et al. Functional reorganization in somatosensory cortical areas 3b and 1 of adult monkeys after median nerve repair: possible relationships to sensory recovery in humans. J Neurosci 1986;6:218–33.
63. Wall JT, Kaas JH. Long-term cortical consequences of reinnervation errors after nerve regeneration in monkeys. Brain Res 1986;372:400–4.
64. Dellon AL, Curtis RM, Edgerton MT. Reeducation of sensation in the hand after nerve injury and repair. Plast Reconstr Surg 1974;53:297–305.
65. Wynn Parry CB. Rehabilitation of the hand. London: Butterworth; 1958.
66. Wynn Parry CB, Salter M. Sensory reeducation after median nerve lesions. Hand 1976;10:63–7.
67. Imai H, Tajima T, Natsumi Y. Successful reeducation of functional sensibility after median nerve repair at the wrist. J Hand Surg Am 1991;16:60–5.
68. Novak CB, Kelly L, Mackinnon SE. Sensory recovery after median nerve grafting. J Hand Surg Am 1992;17:59–68.
69. Rosen B, Lundborg G. Sensory re-education following nerve repair. In: Slutsky DJ, editor. Upper extremity nerve repair - tips and techniques: a Master Skills Publication. Rosemont (VA): American Society for Surgery of the Hand; 2008. p. 159–78.
70. Miller LK, Chester R, Jerosch-Herold C. Effects of sensory reeducation programs on functional hand sensibility after median and ulnar repair: a systematic review. J Hand Ther 2012;25:297–307.
71. Oud T, Beelen A, Eijffinger E, et al. Sensory re-education after nerve injury of the upper limb: a systematic review. Clin Rehabil 2007;21:483–94.
72. Rosen B, Lundborg G. Training with a mirror in rehabilitation of the hand. Scand J Plast Reconstr Surg Hand Surg 2005;39:104–8.
73. Lundborg G, Rosen B, Lindberg S. Hearing as substitution for sensation: a new principle for artificial sensibility. J Hand Surg Am 1999;24:219–24.
74. Rosen B, Bjorkman A, Lundborg G. Improved sensory relearning after nerve repair induced by selective temporary anaesthesia - a new concept in hand rehabilitation. J Hand Surg 2006;31:126–32.
75. Hoang-Kin A, Pegreffi F, Moroni A, et al. Measuring wrist and hand function: common scales and checklists. Injury 2011;42:253–8.
76. Shauver MJ, Chung KC. The minimally clinically important difference of the Michigan Hand Outcome Questionnaire. J Hand Surg Am 2009;34:509–14.
77. Waljee JF, Kim HM, Burns PB, et al. Development of a brief, 12-item version of the Michigan Hand Questionnaire. Plast Reconstr Surg 2011;128:208–20.
78. Levine DW, Simmons BP, Koris MJ, et al. A self-administered questionnaire for the assessment of severity of symptoms and functional status in carpal tunnel syndrome. J Bone Joint Surg Am 1993;75:1585–92.
79. Amadio PC, Silverstein MD, Ilstrup DM, et al. Outcome assessment for carpal tunnel surgery: the relative responsiveness of generic, arthritis-specific, disease-specific and physical examination measures. J Hand Surg Am 1996;21:338–46.
80. Atroshi I, Gummesson C, Johnsson R, et al. Symptoms of disability and quality of life in patients with carpal tunnel syndrome. J Hand Surg Am 1999;24:398–404.
81. Heybeli N, Kutluhan S, Demirci S, et al. Assessment of outcome of carpal tunnel syndrome: a comparison of electrophysiological findings and a self-administered Boston questionnaire. J Hand Surg Am 2002;27:259–64.
82. Mondelli M, Reale F, Sicurelli F, et al. Relationship between the self-administered Boston questionnaire

and electrophysiological findings in follow-up of surgically-treated carpal tunnel syndrome. J Hand Surg Br 2000;25:128–34.
83. Leite JC, Jerosch-Herold C, Song F. A systematic review of the psychometric properties of the Boston Carpal Tunnel Questionnaire. BMC Musculoskelet Disord 2006;7:1–9.
84. Atroshi I, Johnsson R, Nouhan R, et al. Use of outcome instruments to compare workers' compensation and non-workers' compensation carpal tunnel syndrome. J Hand Surg Am 2000; 22:882–8.
85. Ruijs AC, Jaquet JB, Van Riel WG, et al. Cold intolerance following median and ulnar nerve injuries: prognosis and predictors. J Hand Surg Am 2007; 32:434–9.
86. Novak CB, Anastakis DJ, Beaton DE, et al. Cold intolerance after brachial plexus nerve injury. Hand 2012;7:66–71.
87. Stratford P, Gill C, Westaway M, et al. Assessing disability and change on individual patients: a report of a patient specific measure. Physiother Can 1995;47:258–62.
88. Hefford C, Abbot JH, Arnold R, et al. The patient-specific functional scale: validity, reliability, and responsiveness in patients with upper extremity musculoskeletal problems. J Orthop Sports Phys Ther 2012;42:56–65.
89. Novak CB, Anastakis DJ, Beaton DE, et al. Validity of the Patient Specific Functional Scale in patients following upper extremity nerve injury. Hand 2013; 8:132–8.