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REVIEW PAPER

Peripheral nerve injuries in the pediatric population: a review of the literature. Part I: traumatic nerve injuries

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Abstract

Objective This article reviews the clinical results that can be obtained after repair of a traumatic peripheral nerve injury in the pediatric population.

Methods A systematic review of the published literature has been made.

Results Functional outcome after major nerve injuries is sometimes disappointing in adults. However, children have been reported to experience much better functional results after nerve repair than adults. Moreover, recovery generally is faster in children. The superior capacity of children's central nervous system to adapt to external or internal environmental changes (neural plasticity) and the shorter recovery distance from the axon repair site to the target muscle are claimed to be crucial determinants of their favorable outcomes. Moreover, even in the pediatric population, it has been demonstrated that functional results are better the younger the patient is, including better clinical results in those injured in early childhood (< 6 years old) than in those injured in adolescence. Other favorable prognostic factors include the type of nerve injury (with complete transections doing less well than crush injuries) and the timing of surgery (with better outcomes after early repairs).

Conclusions All efforts should be done to repair in a timely and adequate fashion traumatic peripheral nerve injuries in children, as the results are good.

Keywords Peripheral nerve injury · Pediatric patients · Nerve section · Traumatic nerve lesion

Introduction

Every nerve can be injured by localized blunt or sharp trauma, and that injury can be partial or complete, transient or permanent.

Among children, nerve lesions may account for 10 to 15% of the total cases in specialized units [1]. Glass and knife lacerations are the most common causes of traumatic nerve injury in children and adolescents. Many of these penetrating injuries are associated with vascular and/or tendon lacerations. Thin shards of glass and knife blades can penetrate deeply through a minor skin laceration, injuring a nerve. Due to the relatively benign appearance of the skin laceration, if a thorough examination is not done, the nerve injury may go undetected [2]. On the other hand, an accurate, timely diagnosis may result in timely, more effective treatment. For this reason, it is important for examining physicians to perform a tendon and nerve-specific clinical examination of those structures in the region of the laceration. Especially in children, do not expect that the patient will show you or complain of the deficit.

In children, blunt nerve trauma usually results in neurapraxia or minor axonotmesis injuries (Sunderland's first- and second-degree lesions) [3] which recover fully in 95–98% of patients. Nerve recovery may occur within days for minor neurapraxia, but it might take weeks for more significant neurapraxia or axonotmetic injuries. Signs of recovery are an advancing Tinel's sign along the anatomical path of the nerve after a time interval of at least 30 days; initial hypesthesia followed by dysesthesia and then recovering sensation in the anatomic nerve distribution area; and progressive proximal-to-distal anatomic motor recovery. One key is identifying any entrapped, compressed, kinked, or lacerated nerves before irreversible nerve and muscle impairment occurs [2]. Open fractures are at higher risk than closed fractures for nerve entrapment and laceration.

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The functional outcome after major nerve injuries is sometimes disappointing in adults, especially in terms of recovering fine sensory function [4, 5]. However, children have been reported to experience much better functional results after nerve repair than adults [6, 7]. Moreover, recovery generally is faster in children [6].

The superior capacity of children's central nervous system to adapt (neural plasticity) is claimed to be the most crucial determinant of their favorable outcomes, generating high rates of satisfactory recovery [8]. Moreover, even in the pediatric population, it has been demonstrated that functional results are better the younger the patient is, including better clinical results in those injured in early childhood (< 6 years old) than in those injured in adolescence. Children who are injured when very young also are less likely to develop cold intolerance or chronic pain [9, 10].

In addition to the patient's age at the time of their nerve injury, prognostic factors include the type of nerve injury, with complete transections doing less well than crush injuries. Furthermore, the timing of surgery is crucial, with better outcomes after early repairs [5].

Indications for surgery

Clean lacerations caused by a sharp object should be repaired urgently by direct end-to-end repair. If the nerve stumps are blunt and direct repair is impossible without tension, or if the wound is contaminated, nerve repair should be delayed for 3 weeks, most of these cases with a graft.

Displaced fractures and dislocations with neurovascular injury require prompt reduction of the bony displacement. To avoid missing any iatrogenic nerve injuries (entrapment or laceration caused by closed reduction or pin placement), a complete neurological examination should be performed prior to reduction and pinning. Most nerve injuries associated with closed fractures are contusions due to direct trauma from the displaced bone and/or caused by on-going traction ischemia while the nerve is tented, kinked, and/or compressed by the unreduced bone. Once the fracture or dislocation has been reduced, the traction and vascular components of nerve dysfunction disappear. These injuries (contusions) related to bone fracture/dislocation frequently—but not always—resolve over a short period of time with observation alone.

Nerve injuries that do not exhibit signs of recovery by 3 to 6 months post-injury require exploration, decompression, and reconstruction, as appropriate. Failure to recognize an entrapped or lacerated nerve, thereby delaying its repair beyond 6 months, can lead to failed or incomplete recovery and permanent neurological deficits.

Characteristics of injured nerves in children

Upper limb

Ulnar nerve

Ulnar mononeuropathies are the most common upper-extremity mononeuropathies seen in children [11]. The most common etiology is acute trauma, secondary to midshaft or proximal forearm fracture, supracondylar fracture, or elbow dislocation [12].

The ulnar nerve is particularly at risk with elbow dislocation, especially when the medial epicondyle is displaced into the joint [13]. In the forearm, the nerve is at risk of injury, because it lies close to the bone and is tethered above in the cubital tunnel and below by the dorsal cutaneous branch.

Ulnar neuromas-in-continuity without functional muscle activity and good sensory function within the first 6 months post-injury require resection and nerve grafting. A successful outcome following ulnar nerve repair is defined as the recovery of both M4 strength and S4 sensation. In general, proximal injuries do worse than distal ones, as do repairs requiring nerve grafts and those that are delayed [14].

Patient age at the time of repair has been shown to significantly influence outcomes [15, 16]. Chemnitz et al. reviewed the 30-year outcomes of median and ulnar nerve repairs performed in children and adolescents, and found that recovery was significantly better in those who had injuries repaired in childhood (less than 12 years old) than adolescence. On average, children recovered 87% of normal function, compared to 67% of adolescents [5]. The latter figure is similar to or better than findings in adults 5 years after median or ulnar nerve repairs in the forearm [17, 18]. Gaul reported intrinsic motor recovery in 41 patients with an ulnar nerve laceration. Mean key pinch returned to within 86% of normal in younger patients (< 18 years old) [16]. He reported excellent motor results up to the age of 15 years. Bolitho et al. reported the outcomes of 19 children age ≤ 13 years with acute transection injuries to the ulnar nerves that were treated by primary epineural repair, with a mean age at the time of injury of 6.7 years (range, 2–12 years). The site of injury was the palm in four children, wrist in 10, forearm in four, and above elbow in one. The mean level of recovery (using the Medical Research Council scale) of the first dorsal interosseous muscle was grade 4.0 (range, grade 3–5), while the mean outcome for the abductor digiti minimi was grade 3.9 (range, grade 2–5). Mean static 2-point discrimination was 6 mm (range, 2–20 mm). Although proximal injuries (at or above the elbow) exhibited poorer outcomes than more distal injuries, satisfactory function of the intrinsic hand muscles still occurred. Like Chemnitz et al., these authors concluded that epineural repair of an acutely transected ulnar nerve leads to satisfactory recovery of both motor and sensory function in children younger than 13 years [19].

The results presented here indicate that ulnar nerve repair does better in children than in adults, in whom intrinsic recovery seldom occurs with high nerve lesions. Sakellarides reported good to excellent results after ulnar nerve repair in 80% of patients younger than 16 years, but in only 30% of patients 16 and older [20]. Berger et al. [21] and Barrios and de Pablos [7] reported that all their children under 10 years old achieved normal sensory status.

These studies suggest that primary epineural repair of an injured ulnar nerve leads to predictable, satisfactory recovery of both motor and sensory function in childhood. Relative to adults, the level of injury has less impact upon outcome, and good intrinsic motor recovery can be expected. These results also support the contention that age is a major factor affecting outcome.

Intrinsic transfers and rebalancing are appropriate measures for chronic ulnar nerve deficiencies [2].

Radial nerve

Traumatic mechanisms are the most frequent cause of radial neuropathy in children [22]. In this population, supracondylar humeral fractures are more frequent than humeral shaft fractures [22], and radial nerve injury accounts for 5 to 29% of the nerve injuries caused by supracondylar fractures.

Compression injuries may occur subsequent to open reduction of supracondylar fractures [7, 23]. Prolonged retraction during orthopedic surgery also may cause traumatic radial neuropathy [7].

Even though most radial nerve injuries recover spontaneously or represent in-continuity lesions, which are treated with neurolysis [24], nerve repair may be needed in cases involving high-energy trauma and open fractures [25].

Bertelli et al. recommend delaying surgery for a minimum of 6 months to allow for spontaneous recovery, thereby avoiding unnecessary neurolysis [25]. On the other hand, Barrios and de Pablos noted that a worse prognosis was associated with delayed surgical nerve repair, particularly when the time interval between nerve damage and surgery is more than 1 year [7].

Bertelli et al. published their results performing radial nerve grafting in seven children, of mean age 6 years (range, 4–11 years), who had sustained a radial nerve injury following a distal humeral fracture. The mean interval between injury and surgery was 6.7 months (range, 6–9 months). The radial nerve was entrapped within the fracture site in two patients, while it was completely interrupted without entrapment in five. All patients ultimately obtained full active wrist extension with grade M4 strength. For finger extension, all patients again were graded M4, obtaining full metacarpophalangeal finger and thumb extension, with the wrist in neutral in three patients and fully extended in four. During the thumbs-up test, four patients achieved complete extension of all thumb joints, while three exhibited metacarpophalangeal extension lag, averaging 30°. The authors demonstrated that nerve grafting of radial nerve injuries in children at the level of the distal humerus within 8 months of their injury can yield excellent outcomes, whereas only 15% of intermediate radial lesions achieve good results in adults [25, 26]. The authors also reviewed the literature and identified only seven pediatric cases similar to their own. Of these seven published pediatric patients who underwent radial nerve grafting, four experienced functional recovery, while three had virtually no recovery. One of the patients with no recovery was operated upon 51 months post-injury.

Chronic radial neuropathies require tendon transfers to improve grip and key pinch function.

Isolated posterior interosseous nerve injury can occur in patients with a Monteggia fracture/dislocation [27]. It is also a risk during operations to treat fractures of the proximal radius [13]. Chronic posterior interosseous palsies can be treated by tendon or nerve transfer. Median nerve transfers to the posterior interosseous nerve and nerves to the wrist extensors have been successful at restoring wrist, finger, and thumb extension [28, 29].

Musculocutaneous nerve

Isolated musculocutaneous nerve (MCN) injuries are extremely rare, because most lesions involving this nerve are associated with a brachial plexus injury [30].

In the 28 cases of musculocutaneous nerve involvement reported by Worster-Drought in 1921, in his series of 1008 peripheral nerve injuries from the first world war, in only one patient was there damage to the MCN alone [31]. In 1910, Osann reviewed the isolated MCN palsies published since 1876 and added one case of his own. Of the 19 lesions he identified, 11 were of traumatic origin [32].

It has been reported that an isolated pure MCN lesion can occur secondary to violent extension of the forearm [31]. As the MCN runs along a straight course and is fixed at the coracobrachialis muscle by branches to the biceps and brachialis muscles at the point where the MCN penetrates the deep fascia at the elbow, violent extension of the forearm could result in overstretching of the nerve [33]. In this one reported case, the nerve was sectioned.

Median nerve

Median nerve injuries are frequently associated with a supracondylar fracture and elbow dislocation, alone or combined with a radial and/or ulnar nerve injury [34]. The median and ulnar nerve are the nerves most frequently injured with fractures of "the elbow" [7]. The elbow is a region that poses difficulty, when treating nerve injuries, especially in children. The close proximity to bone of all the trunks makes them vulnerable [13]. Nerve lesions in-continuity are the most common operative finding in nerve palsies following elbow trauma in children [1]. Many times, nerves are damaged during surgery by failure to relieve compression or entrapment.

In cases of supracondylar fracture, the median nerve is often entrapped with the brachial artery [13]. It is very important to explore the nerve and the artery in these patients to ensure that adequate circulation is restored, thereby avoiding ischemia, a compartmental syndrome, and the consequent and very difficult to treat Volkmann's contracture. Persistent neuropathic pain or worsening of a nerve deficit after reduction of a fracture, both indicate impending ischemia [13]. Fractures of the forearm can be associated with median nerve injury, usually secondary to compression and ischemia. Protection by flexor muscles and the nerve's midline course generally reduce the likelihood of nerve laceration by bone fragments [13]. Median nerve injuries from supracondylar fractures are most commonly neurapraxic [35].

As previously cited in the current review, Chemnitz et al. assessed the outcomes of 45 patients at a median of 31 years after a complete median and/or ulnar nerve injury in the forearm [5]. Functional recovery was significantly better after injuries sustained during childhood (under age 12) than after those that occurred during adolescence (12 to 20 years of age), with 87% and 67% of patients experiencing complete recovery, respectively. No significant differences in recovery were observed between median and ulnar nerve injuries, or when both nerves were injured. Motor function was close to normal, and cold sensitivity was not a problem in either age group. The median DASH scores were within normal limits and did not differ between the groups. This finding is contrary to those reported for studies of adults who sustained such injuries, in whom a considerable level of disability was noted [36]. Relative to younger-age injuries, patients who sustained their injury in adolescence claimed that their nerve injury had a significantly larger adverse effect on their profession, education, and leisure activities [5]. In this same study, nerve injuries in the forearm (median or ulnar nerve) of a growing child did not affect final (adult) hand size, even when both nerves were injured, contrary to the hand size difference frequently observed in patients with a brachial plexus birth palsy [37]. In truth, there may be some minor size difference after a median or an ulnar nerve injury in childhood; but visual inspection is usually insufficient to detect it [5].

One of the most important objectives of treating a median nerve injury is to recover hand sensation. Lundborg and Rosen assessed tactile gnosis in 54 patients (mean age 32; range 4–72) after median or ulnar nerve transections at the wrist level. They identified a well-delineated critical period for sensory relearning after nerve repair, with optimum capacity below age 5–10 years, followed by a rapid decline that levels out 18 years old [8].

Median neuromas-in-continuity that do not provide functional muscle activity and good sensory function within the first 6 months post-injury require resection and nerve grafting. [2]. Opposition and flexor pollicis longus/flexor digitorum profundus II transfers are appropriate for treating chronic median neuropathies.

Distal median nerve injuries have been described in neonates due to puncture of the radial artery, simulating carpal tunnel syndrome [38].

Anterior interosseous nerve

Anterior interosseous nerve syndrome has been reported in several children, associated with a supracondylar fracture of the humerus [39], but it is not usually an isolated nerve palsy [13]. This nerve is particularly susceptible to ischemia and even anoxia because of its location deep within the flexor compartment [13].

Patients with this syndrome present with spontaneous pain anteriorly in their elbow associated with weak flexion of the terminal joints of the thumb and index fingers, resulting in a weak pincer grip. Surgery is indicated if spontaneous recovery is not evident after several months.

Pape et al. reported a high incidence of damage to the median nerve in the antecubital fossa due to blood sampling in preterm infants [40]. In a significant proportion, permanent functional nerve damage occurred.

Axillary nerve

Traumatic axillary nerve injuries are associated with shoulder dislocations in children, and with proximal humeral fractures [41–43]. The brachial plexus also can be injured in patients with a proximal humeral fracture.

Digital nerve lacerations

Sharp digital nerve lacerations that are diagnosed and treated within 3 weeks of injury have an outstanding chance of full sensory recovery in children and adolescents [13]. Lacerations diagnosed later can go on to full recovery, but some may require nerve grafting to achieve tension-free repair [2]. The repair of digital nerve lacerations is important, regardless of the time interval since injury, because neuromas can be painful and functionally limiting. This is even more crucial in children, who do so well in terms of sensory recovery.

The recovery of cutaneous sensation after repairing digital nerves is often remarkably good in infants and children, and much better than in adults, making this an example of the importance of age as a prognostic factor for nerve repairs [13].

Several studies of digital nerve repairs have demonstrated a strong inverse correlation between a patient's age and level of sensory recovery [44–46], with younger age predicting greater recovery.

Lower limb

The prognosis for nerves injured by fractures and dislocations in the lower limb is much worse than it is for the upper limb, probably because of the greater forces necessary to fracture or dislocate the pelvis and fracture the long bones of the lower limbs [13].

Sciatic nerve

Sciatic nerve injuries are among the most frequent traumatic neuropathies in children. In the past, a misplaced injection in the buttock was the most common cause. Fortunately, this type of traumatic sciatic nerve injury has decreased in frequency [12]. The nerve also can suffer stretch injuries during breech deliveries [47].

The most frequent etiology is traumatic, with the peroneal division more commonly affected than the tibial division, in the absence of penetrating trauma.

The sciatic nerve may be lacerated or crushed in accidents. It also may be compressed or directly injured during operations in the hip region, during closed reduction of a hip dislocation, and from forcible stretching of the hamstrings to relieve contractures [48].

With proximal lesions of the sciatic nerve, the peroneal division is more frequently affected than the tibial division. This may be because the vascular supply to the peroneal division may be more susceptible to compromise from stretch or compression [12].

Surgical exploration should be undertaken immediately when lacerations are suspected. In patients with a lesion-in-continuity, surgical exploration can be deferred until 6 months after trauma, to see if significant spontaneous recovery of nerve function will occur. If not, surgical repair is indicated.

Common peroneal nerve

Traumatic common peroneal nerve injuries can result from direct trauma to the nerve at the fibular head [49], and they can be associated with orthopedic manipulations involving the knee. It must be emphasized that meticulous protection of the peroneal nerve at the fibular head is absolutely necessary in children undergoing an orthopedic procedure [50].

Stretch injuries related to ankle inversion is another traumatic mechanism of peroneal nerve injury in children [50, 51].

Sural nerve

Sural nerve injuries have been described due to accidental lacerations and ankle fractures in children [48].

Lumbar plexus injury

Several cases of birth injury involving the lumbosacral plexus have been reported in the literature. These lesions are very rare, contrary to the high frequency of brachial plexus damage in newborns [52]. They are related to sustained or excessive lumbosacral traction during breech delivery. Recovery in these cases is typically incomplete.

The most frequent causes of traumatic lumbosacral plexus palsy in children are blunt abdominal trauma in the context of motor vehicle accidents, pelvic fractures and gunshot wounds [53, 54].

Neuropathies associated with limb-lengthening procedures

Neuropathies in the setting of limb lengthening are not uncommon, but they are frequently subclinical.

Tibial lengthening procedures are associated with a peroneal much more frequently than tibial neuropathy [12]. Femoral lengthening can place the sciatic nerve at risk, particularly the peroneal division. Mixed-nerve somatosensory-evoked potentials have been used to monitor distraction during lengthening procedures [55–57].

Burn-associated neuropathies

Children with extensive burns are at increased risk of peripheral neuropathies [58]. Mechanisms include direct nerve tissue destruction from the burn, extensive edema with compartment syndrome, critical illness polyneuopathy caused by systemic mediators, and entrapment neuropathies caused by scarring. The incidence of neuropathy exceeds 10% in many series [12].

Thermal injuries also can induce an inflammatory cascade that results in nerve dysfunction [12].

Conclusions

Children have biologic advantages relative to adults, and these advantages are highly apparent in those who present with nerve injuries. Improved outcomes in children have been attributed to the shorter recovery distance from the axon repair site to the muscle target, accelerated nerve growth, and increased brain plasticity, allowing for better incorporation of aberrant sensory input.

Full recovery is expected in nearly all injuries associated with blunt trauma, as well as with nerve lacerations that undergo immediate skillful primary repair. Even late repair with neuroma resection and nerve grafting and nerve transfers can yield very good results.

Although many injuries recover spontaneously, it is very important to identify those injuries that require nerve repair and will not recover on their own, since the most significant determinant of prognosis is delay in surgical treatment.

Aggressive surgical management is better than mere observation for injuries that are not recovering as expected, due to the good results that can be expected even with proximal injuries. Adequate follow-up also is essential to detect and treat progressive deformities caused by chronic nerve deficits.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Birch R, Achan P (2000) Peripheral nerve repairs and their results in children. Hand Clin 16:579–595
2. Waters PM, Bae DS (2012) Traumatic peripheral nerve injuries. In: Pediatric hand and upper limb surgery: a practical guide. Springhouse Publishing Co, U.S.
3. Sunderland S (1951) A classification of peripheral nerve injuries producing loss of function. Brain J Neurol 74:491–516
4. Galanakos SP, Zoubos AB, Ignatiadis I, Papakostas I, Gerostathopoulos NE, Soucacos PN (2011) Repair of complete nerve lacerations at the forearm: an outcome study using Rosén-Lundborg protocol. Microsurgery 31:253–262. https://doi.org/10.1002/micr.20845
5. Chemnitz A, Björkman A, Dahlin LB, Rosén B (2013) Functional outcome thirty years after median and ulnar nerve repair in childhood and adolescence. J Bone Joint Surg Am 95:329–337. https://doi.org/10.2106/JBJS.L.00074
6. Tajima T, Imai H (1989) Results of median nerve repair in children. Microsurgery 10:145–146
7. Barrios C, de Pablos J (1991) Surgical management of nerve injuries of the upper extremity in children: a 15-year survey. J Pediatr Orthop 11:641–645
8. Lundborg G, Rosén B (2001) Sensory relearning after nerve repair. Lancet Lond Engl 358:809–810. https://doi.org/10.1016/S0140-6736(01)06001-9
9. Atherton DD, Taherzadeh O, Elliot D, Anand P (2008) Age-dependent development of chronic neuropathic pain, allodynia and sensory recovery after upper limb nerve injury in children. J Hand Surg Eur Vol 33:186–191. https://doi.org/10.1177/1753193408087029
10. Stevenson JH, Zuker RM (1986) Upper limb motor and sensory recovery after multiple proximal nerve injury in children: a long term review in five patients. Br J Plast Surg 39:109–113
11. Felice KJ, Royden Jones H (1996) Pediatric ulnar mononeuropathy: report of 21 electromyography-documented cases and review of the literature. J Child Neurol 11:116–120. https://doi.org/10.1177/088307389601100211
12. Mc Donald CM (2015) Electrodiagnosis in pediatrics. In: Alexander MA, Matthews DJ (eds) Pediatric rehabilitation. principles and practice, Fifth edn. Demos Medical Publishing, New York, pp 113–152
13. Birch R (2011) Surgical disorders of peripheral nerves, 2nd edn. Springer-Verlag, London
14. Woo A, Bakri K, Moran SL (2015) Management of ulnar nerve injuries. J Hand Surg 40:173–181. https://doi.org/10.1016/j.jhsa.2014.04.038
15. Ruijs ACJ, Jaquet J-B, Kalmijn S, Giele H, Hovius SER (2005) Median and ulnar nerve injuries: a meta-analysis of predictors of motor and sensory recovery after modern microsurgical nerve repair. Plast Reconstr Surg 116:484–494 discussion 495–496
16. Gaul JS (1982) Intrinsic motor recovery–a long-term study of ulnar nerve repair. J Hand Surg 7:502–508
17. Lundborg G, Rosén B, Dahlin L et al (2004) Tubular repair of the median or ulnar nerve in the human forearm: a 5-year follow-up. J Hand Surg Edinb Scotl 29:100–107. https://doi.org/10.1016/j.jhsb.2003.09.018
18. Strickland JW, Idler RS, DelSignore JL (1991) Ulnar nerve repair. In: Gelberman RH (ed) Operative nerve repair and reconstruction. JB Lippincott, Philadelphia, pp 425–436
19. Bolitho DG, Boustred M, Hudson DA, Hodgetts K (1999) Primary epineural repair of the ulnar nerve in children. J Hand Surg 24:16–20. https://doi.org/10.1053/jhsu.1999.jhsu25a0016
20. Sakellarides H (1962) A follow-up study of 172 peripheral nerve injuries in the upper extremity in civilians. J Bone Joint Surg Am 44-A:140–148
21. Berger A, Mailänder P (1991) Advances in peripheral nerve repair in emergency surgery of the hand. World J Surg 15:493–500
22. Escolar DM, Jones HR (1996) Pediatric radial mononeuropathies: a clinical and electromyographic study of sixteen children with review of the literature. Muscle Nerve 19:876–883. https://doi.org/10.1002/(SICI)1097-4598(199607)19:7<876::AID-MUS10>3.0.CO;2-H
23. Pollock FH, Drake D, Bovill EG, Day L, Trafton PG (1981) Treatment of radial neuropathy associated with fractures of the humerus. J Bone Joint Surg Am 63:239–243
24. Amillo S, Mora G (1999) Surgical management of neural injuries associated with elbow fractures in children. J Pediatr Orthop 19:573–577
25. Bertelli J, Soldado F, Ghizoni MF (2018) Outcomes of radial nerve grafting in children after distal humerus fracture. J Hand Surg. https://doi.org/10.1016/j.jhsa.2018.04.018
26. Shergill G, Bonney G, Munshi P, Birch R (2001) The radial and posterior interosseous nerves. Results of 260 repairs. J Bone Joint Surg (Br) 83:646–649
27. Jessing P (1975) Monteggia lesions and their complicating nerve damage. Acta Orthop Scand 46:601–609
28. Brown JM, Tung THH, Mackinnon SE (2010) Median to radial nerve transfer to restore wrist and finger extension: technical nuances. Neurosurgery 66:75–83; discussion 83. https://doi.org/10.1227/01.NEU.0000354364.13224.C8
29. Ustün ME, Ogün TC, Büyükmumcu M (2001) Neurotization as an alternative for restoring finger and wrist extension. J Neurosurg 94:795–798. https://doi.org/10.3171/jns.2001.94.5.0795
30. Jones HR (1986) Compressive neuropathy in childhood: a report of 14 cases. Muscle Nerve 9:720–723. https://doi.org/10.1002/mus.880090807
31. Trojaborg W (1976) Motor and sensory conduction in the musculocutaneous nerve. J Neurol Neurosurg Psychiatry 39:890–899
32. Osann E (1910) Beitrag zur Kenntnis der isolierten Lahmung des N. musculo-cutaneus. Dtsch Med Wochenschr 36:832–835
33. Sunderland S (1968) Nerves and nerve injuriese. Livingstone, Edinburgh, pp 358–396
34. Babal JC, Mehlman CT, Klein G (2010) Nerve injuries associated with pediatric supracondylar humeral fractures: a meta-analysis. J Pediatr Orthop 30:253–263. https://doi.org/10.1097/BPO.0b013e3181d213a6
35. Culp RW, Osterman AL, Davidson RS, Skirven T, Bora FW Jr (1990) Neural injuries associated with supracondylar fractures of the humerus in children. J Bone Joint Surg Am 72:1211–1215

36. Novak CB, Anastakis DJ, Beaton DE, Katz J (2009) Patient-reported outcome after peripheral nerve injury. J Hand Surg 34: 281–287. https://doi.org/10.1016/j.jhsa.2008.11.017
37. Nath RK, Karicherla P, Mahmooduddin F (2010) Shoulder function and anatomy in complete obstetric brachial plexus palsy: long-term improvement after triangle tilt surgery. Childs Nerv Syst ChNS Off J Int Soc Pediatr Neurosurg 26:1009–1019. https://doi.org/10.1007/s00381-010-1174-2
38. Koenigsberger MR, Moessinger AC (1977) Iatrogenic carpal tunnel syndrome in the newborn infant. J Pediatr 91:443–445
39. Spinner M, Schreiber SN (1969) Anterior interosseous-nerve paralysis as a complication of supracondylar fractures of the humerus in children. J Bone Joint Surg Am 51:1584–1590
40. Pape KE, Armstrong DL, Fitzhardinge PM (1978) Peripheral median nerve damage secondary to brachial arterial blood gas sampling. - PubMed - NCBI. J Pediatr 93:852–856
41. Drew SJ, Giddins GE, Birch R (1995) A slowly evolving brachial plexus injury following a proximal humeral fracture in a child. J Hand Surg Edinb Scotl 20:24–25
42. Berry H, Bril V (1982) Axillary nerve palsy following blunt trauma to the shoulder region: a clinical and electrophysiological review. J Neurol Neurosurg Psychiatry 45:1027–1032
43. Liveson JA (1984) Nerve lesions associated with shoulder dislocation; an electrodiagnostic study of 11 cases. J Neurol Neurosurg Psychiatry 47:742–744
44. al-Ghazal SK, McKiernan M, Khan K, McCann J (1994) Results of clinical assessment after primary digital nerve repair. J Hand Surg Edinb Scotl 19:255–257
45. Chaise F, Friol JP, Gaisne E (1993) Results of emergency repair of wounds of palmar collateral nerves of the fingers. Rev Chir Orthop Reparatrice Appar Mot 79:393–397
46. Efstathopoulos D, Gerostathopoulos N, Misitzis D, Bouchlis G, Anagnostou S, Daoutis NK (1995) Clinical assessment of primary digital nerve repair. Acta Orthop Scand Suppl 264:45–47
47. Sriram K, Sakthivel A (1981) Sciatic nerve palsy in the new born. Ann Acad Med Singap 10:472–475
48. Ouvrier RA, Shield L (1999) Focal lesions of peripheral nerves. In: Ouvrier RA, Mcleod JG, Pollard JD (eds) Peripheral neuropathy in childhood. MacKeith Press, London
49. Levin KH, Wilbourn AJ, Jones HR (1991) Childhood peroneal neuropathy from bone tumors. Pediatr Neurol 7:308–309
50. Jones HR, Felice KJ, Gross PT (1993) Pediatric peroneal mononeuropathy: a clinical and electromyographic study. Muscle Nerve 16:1167–1173. https://doi.org/10.1002/mus.880161105
51. Wang J-C, Chan R, Yang T-F (2014) Delayed onset of peroneal neuropathy after minor ankle torsion in a 9-year-old boy. J Child Neurol 29:843–845. https://doi.org/10.1177/0883073813477688
52. Hope EE, Bodensteiner JB, Thong N (1985) Neonatal lumbar plexus injury. Arch Neurol 42:94–95
53. Egel RT, Cueva JP, Adair RL (1995) Posttraumatic childhood lumbosacral plexus neuropathy. Pediatr Neurol 12:62–64
54. Chiou-Tan FY, Kemp K, Elfenbaum M et al (2001) Lumbosacral plexopathy in gunshot wounds and motor vehicle accidents: comparison of electrophysiologic findings. Am J Phys Med Rehabil 80: 280–285 quiz 286–288
55. Makarov MR, Samchukov ML, Birch JG, Cherkashin AM, Sparagana SP, Delgado MR (2012) Somatosensory evoked potential monitoring of peripheral nerves during external fixation for limb lengthening and correction of deformity in children. J Bone Joint Surg (Br) 94:1421–1426. https://doi.org/10.1302/0301-620X.94B10.28913
56. Polo A, Zambito A, Aldegheri R, Tinazzi M, Rizzuto N (1999) Nerve conduction changes during lower limb lengthening. Somatosensory evoked potentials (SEPs) and F-wave results. Electromyogr Clin Neurophysiol 39:139–144
57. Polo A, Aldegheri R, Zambito A, Trivella G, Manganotti P, de Grandis D, Rizzuto N (1997) Lower-limb lengthening in short stature. An electrophysiological and clinical assessment of peripheral nerve function. J Bone Joint Surg (Br) 79:1014–1018
58. Marquez S, Turley JJ, Peters WJ (1993) Neuropathy in burn patients. Brain J Neurol 116(Pt 2):471–483