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Functional reconstruction of lower extremity nerve injuries

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Abstract

Peripheral nerve injuries (PNI) in the lower extremity are an uncommon but highly morbid condition. Recent advances in our understanding of nerve physiology and microsurgical techniques have inspired renewed faith in nerve surgery and sparked a creative renaissance in the tools, approaches, and reconstructive schemas available to surgeons in the management of lower extremity PNIs. In this article, we review the literature and provide a principles-based approach for the surgical management of lower extremity PNIs with an emphasis on techniques for functional reconstruction after complete nerve injury. General principles in management include early diagnosis with electrodiagnostics and imaging, early surgical exploration, and opting for nerve and tendon transfers when primary reconstruction of the injured nerve is unfavorable (e.g., delayed reconstruction, unavailability of proximal or distal nerve stumps, or long regenerative distance). The goal of functional reconstruction should be to restore independent gait, so understanding the roles of major neuromuscular units during the gait cycle informs the selection of donor nerves and tendons for transfer. Based on these principles and literature to date, specific algorithms for surgical management are presented for femoral, sciatic, tibial, and common peroneal nerves. We recognize limitations of the current literature, namely the predominance of case series evidence, and call for the accrual of more patient data in surgical management of PNIs.

Keywords: Nerve, nerve transfer, tendon transfer, gait

INTRODUCTION

Peripheral nerve injuries (PNI) in the lower extremity are an uncommon but highly morbid condition, usually resulting from traumatic or iatrogenic injury. In the civilian trauma setting, PNIs occur in 1.8%-2.8% of extremity injuries, of which 23%-40% are of the lower extremity[1,2]. Injuries to the peroneal and sciatic nerves are the most common, accounting for more than two-thirds of cases. In the modern military setting, the relative incidence of tibial nerve injuries increases to match that of peroneal nerve injuries, likely reflecting the impact of improvised explosive devices causing a broader zone of injury[3]. Beyond trauma, the incidence of iatrogenic nerve injury should not be underestimated, accounting for 10%-17% of all PNIs, including those in the lower extremities[4,5]. Timely recognition and management PNIs are the primary barriers to better outcomes[6].

Many factors differentiate nerve reconstruction in the lower *vs.* upper extremity. First, the nature of lower extremity injuries tends to be more severe, often resulting in large segmental nerve defects. Second, regenerative distances can be much greater with few donor nerves available for distal transfers. Finally, the goals of nerve reconstruction in the lower *vs.* upper extremities differ in a number of ways. Unlike the upper extremity, where dexterity and fine discriminiative sensation are valued, reconstruction of the lower extremity prioritizes the restoration of stable, painless gait and protective sensation. Historically, nerve reconstructions were rarely performed because little was known about how to accurately diagnose and surgically manage these injuries[7-9]. However, recent advances in our understanding of nerve physiology and microsurgical techniques have inspired renewed faith in nerve surgery and sparked a creative renaissance in the tools, approaches, and reconstructive schemas available to surgeons in the management of lower extremity PNIs.

The optimal reconstructive strategy for PNIs often depends on what is observed during the exploration of the injured nerve. A broad understanding of the available interventions facilitates successful pre-surgical planning, patient counseling, and intra-operative decision-making. In this review, we provide a principles-based approach for the surgical management of lower extremity nerve injuries with an emphasis on techniques for functional reconstruction after complete nerve injury.

DIAGNOSIS AND EVALUATION

Outcomes are highly dependent on the timeliness and accuracy of diagnosis. History-taking should determine the timing and mechanism of injury, rapidity of onset of symptoms, and functional deficits. Open injuries with acute onset of numbness or weakness are typically explored and repaired immediately, particularly when concomitant vascular, orthopedic or soft tissue injuries require immediate surgical intervention. Crush or high-energy injuries are associated with a wide zone of nerve injury and should be explored in a delayed manner to allow the extent of tissue damage to declare. Depending on the rapidity of onset, progressive weakness suggests a compression neuropathy from mass effect (e.g., tumor or hematoma), muscular or ligamentous compression, or osmotic edema (e.g., diabetes). The degree and distribution of functional loss will hint at the degree of injury to nerve architecture (neuropraxia *vs.* axonotmesis *vs.* neurotmesis) as well as localization of the lesion. Finally, the history should also identify any patient characteristics or comorbidities that may affect outcomes, such as their self-efficacy and alacrity for rehabilitation, prior surgeries or radiation that may render a less favorable tissue bed, diabetes, peripheral vascular disease, and smoking. The patient's age is an important consideration that will influence surgical decision making, as regenerative potential is known to decline with age.

A detailed sensory and motor exam should be performed to characterize the degree of nerve injury and localize the lesion. Sensory exam should include light touch, sharp-dull sensation, two-point discrimination, and monofilament testing. The presence of neuropathic pain and evaluation for a symptomatic neuroma can also be helpful in localizing lesions. Pain in a defined neural anatomic distribution, a positive Tinel sign, and a positive response to local anesthetic injection all increase the likelihood of a sensory neuroma indicating nerve injury[10]. Motor exam should utilize the Medical Research Council (MRC) grading system, and should be assessed across the hip, knee, ankle, and toes in all planes of active motion. Additional exam maneuvers that help further localize the lesion include searching for a Tinel sign along an injured nerve and straight leg raise and reflex testing to identify lumbosacral radiculopathies. Finally, observation of gait may identify stereotypical associations with patterns of PNI and help contextualize the deficits. In cases of unclear or absent injury and inconsistent localization of the neurologic lesion, functional neurological exam maneuvers may identify psychogenic weakness and avoid unnecessary surgery. One such test is Hoover's sign, in which psychogenic weakness of hip extension is revealed when the involuntary, forceful hip extension is elicited during voluntary flexion of the contralateral hip[11].

Electrodiagnostics and imaging are helpful in localizing and characterizing the extent of nerve injury. Serial electrodiagnostic testing can inform on the degree of reinnervation, or the lack thereof, to aid surgical decision making. In the senior author's practice, it is standard to obtain a nerve conduction study and electromyography at 2-3 months after injury, at which point Wallerian degeneration has occurred and electrical abnormalities will be detectable. A loss of distal conduction or the presence of fibrillations and positive sharp waves within the affected muscle groups indicates critical axonal loss and denervation[12]. Either magnetic resonance or ultrasound imaging has become standard tools used in the workup of traumatic nerve injuries, as they provide valuable information regarding gross nerve morphology and architecture to help differentiate partial and complete injuries. Magnetic resonance neurography (MRN) protocols are gaining ground as a powerful mode of nerve imaging, achieving finer resolution at the fascicular level[13,14]. However, sensitivity for MRN in detected closed nerve injuries is only 40%-70%, meaning that workup should not be precluded by a normal or negative MRN study[15,16]. Ultrasound can be an inexpensive and useful method for diagnosing injuries to more superficial nerves, such as the common peroneal nerve (CPN), but the efficacy of this imaging modality remains user and institutional dependent.

GENERAL TREATMENT PRINCIPLES

Watchful waiting with close observation for clinical or electrodiagnostic evidence of recovery is appropriate in certain clinical scenarios in which the potential exists for spontaneous recovery. In general, this is the preferred management for closed nerve injuries in which there is no evidence of nerve transection or gross injury on imaging. Physical therapy should be initiated during this observation period when possible, including braces and passive range of motion exercises to prevent contractures while deficits persist. Surgical intervention is typically indicated if no clinical functional recovery or electrodiagnostic evidence of reinnervation is observed 3-5 months following injury.

When exploring a closed nerve injury in a delayed fashion, the surgeon should be prepared to employ different surgical approaches depending on the specific findings that are encountered. If nerve macroarchitecture is preserved and there is no visible injury identified along the traumatized nerve, then exploration should be limited to neurolysis and release of distant compression sites. Neurolysis can be "external" - release of fibrotic tissue around the epineurium - or "internal" - release of interfascicular fibrotic tissue. While the exact mechanisms of neurolysis leading to improved function are not well described, the alleviation of compressing forces is thought to facilitate axonal transport, perineural vascular flow, myelination, and axonal regeneration, enabling more rapid and robust reinnervation of target muscles[17,18].

Neurolysis of common compression sites may augment functional recovery. Decompression relieves any existing insult to the nerve and prevents the development of new compression neuropathies as a result of PNI induced neural edema - perhaps limiting axonal injury and clinical symptoms under the double crush hypothesis[19].

One of the most challenging clinical scenarios is a nerve injury in continuity. We currently lack intraoperative tools to ascertain the presence of viable axons regenerating beyond the injury site that have yet to synapse with end organs. We therefore must rely on clinical assessment of the nerve appearance and its consistency on palpation. A bulbous segment of nerve tissue that is firm and pale is suggestive of a neuroma in continuity. This is classified as an axonotmetic injury with partial or complete damage to the internal architecture of the nerve (Sunderland grade II-IV) that can impede spontaneous regeneration beyond the injury. If a large neuroma-in-continuity affecting the entire diameter of the nerve is encountered, complete excision to healthy appearing fascicles followed by interposition nerve grafting is typically indicated. If a partial neuroma-in-continuity is encountered, perhaps with some muscle contractions elicited by direct electrical stimulation proximal to the injury site, an internal neurolysis can be considered to free intact fascicles and reconstruct only the injured portions of the nerve. However, the surgeon should proceed with caution so as not to downgrade any baseline function or remove the potential for spontaneous recovery. In the scenario of a partial neuroma-in-continuity, it is often wise to avoid surgical interventions at the injury site and consider distal end-to-side nerve transfers when these options are available.

When one encounters a complete neuroma-in-continuity or nerve transection, resection and nerve reconstruction are indicated if the lesion is thought to be causing neuropathic pain. If the patient is not experiencing pain originating from that lesion, the surgeon must consider whether nerve reconstruction has the potential to restore motor or sensory function and whether the benefit and likelihood of success outweighs the ensuing deficits created from harvesting nerve graft or nerve transfers. Intraoperative neural monitoring and electrodiagnostics are particularly useful in this setting, as the absence of nerve action potentials across the neuroma in continuity would motivate resection and reconstruction over neurolysis alone[20-22]. However, the potential for successful reconstruction depends on the likelihood of innervation prior to advanced denervation-induced atrophy. With time, denervated muscle undergoes progressive, irreversible atrophy with fibrosis and degradation of myofibers and motor endplates[23,24]. As such, surgeons must consider the time elapsed since injury, the regenerative distance, and the innate regenerative capacity of the patient based on age and comorbidities. Assuming that nerves regenerate at a rate of roughly 1 mm per day or 1 inch per month and that reinnervation must occur within 18 months of denervation, the regenerative distance for a proposed surgical plan can be used to determine the favorability for meaningful motor recovery [Figure 1][25]. If the regeneration distance is favorable, then primary repair or secondary grafting should generally be attempted.

The advent of distal nerve transfers expanded the window of opportunity in which surgical intervention can be considered by decreasing the regenerative distances required to reinnervate target muscle groups. This requires the availability of a healthy donor nerve with redundant or expendable function in close enough proximity to allow for an end-to-end or end-to-side coaptation sufficiently distal to the site of injury. When performing nerve transfers, the donor nerve should be transected as distally as possible to facilitate a tension-free distal coaptation to the recipient nerve and the recipient nerve should be transected as proximally as needed to provide additional redundancy if needed. If the redundancy is not needed, the recipient nerve stump is typically trimmed to prioritize a distal repair, minimizing the regenerative distance. Donor nerve selection should also be mindful of any agonism/antagonism vis-a-vis the function to be

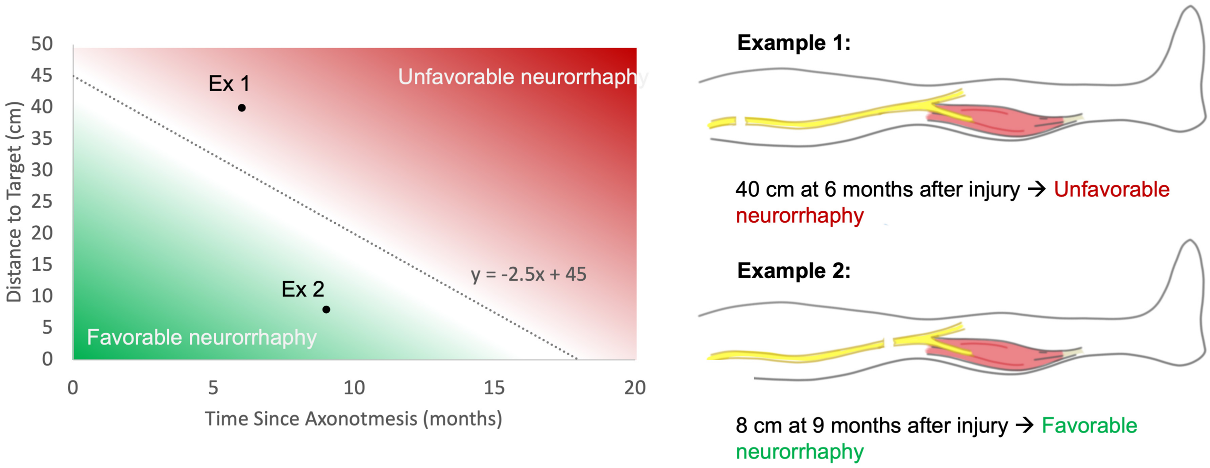

Figure 1. Rule-of-thumb calculation for predicting outcomes after neurorrhaphy. Assuming that axonal regeneration occurs at a rate of 2.5 cm per month and that the neuromuscular junction will remain intact for 18 months, favorable neurorrhaphies are those in which the distance between the injury site to the muscle target is less than 45 - 2.5x in centimeters, where x is the number of months since injury. In example 1, primary repair at 6 months after high sciatic nerve injury is unfavorable and nerve transfers should be considered. In example 2, primary repair at 9 months of a low sciatic nerve injury is favorable.

restored. Again, the regeneration distance and timing of intervention should be such that the reinnervation of the target muscles occurs expeditiously to maximize motor recovery[26].

Finally, when nerve reconstruction or distal nerve transfers cannot be expected to produce meaningful functional recovery for the consideration discussed above, tendon transfers can be considered. The following sections describe complex nerve and tendon transfers for functional reconstruction of specific nerves in the lower extremity.

Reconstruction of femoral nerve injury

Injury to the femoral nerve results in deficits of hip flexion, knee extension, and sensation to the anterolateral thigh and leg. Generally, hip flexion is largely preserved due to activity of the iliopsoas, which is innervated by the lumbosacral plexus, but knee extension is severely impacted. In the gait cycle, knee extension is most important in preparation for heel strike and into early stance as it stabilizes the knee while the body's center of gravity lies posterior to the joint axis [Figure 2]. Even when a patient has satisfactory gait on a flat surface, patients with quadricep weakness may still have difficulty with stairs, inclines, and standing from a chair. Therefore, the goals of reconstruction are to stabilize the knee and restore forceful knee extension to enable walking and transferring from a seated position.

Our approach to femoral nerve reconstruction depends primarily on the availability of proximal and distal nerve stumps, the length of the defect, and the amount of time that has elapsed since injury [Figure 3]. In general, repair of the nerve with or without grafts should be considered when timely intervention is possible, because regeneration distances are relatively short in the thigh. However, in many scenarios, including delayed repair, large segmental defects, or very proximal nerve injury (i.e., retroperitoneal tumor resection), nerve transfers offer the best chance for meaningful functional recovery. When available, the obturator nerve offers the best donor nerve to address femoral nerve injuries, with ample length to achieve tension free end-to-end or supercharged end-to-side transfers[27]. As described in 2010 by Campbell *et al.*[28], the obturator to femoral nerve transfer has since been utilized, modified, and described many times in the literature with good consistency of outcomes, typically achieving MRC grade 4 or better[28-31]. The technique usually involves transferring the gracilis branch to a large motor division supplying the rectus femoris and

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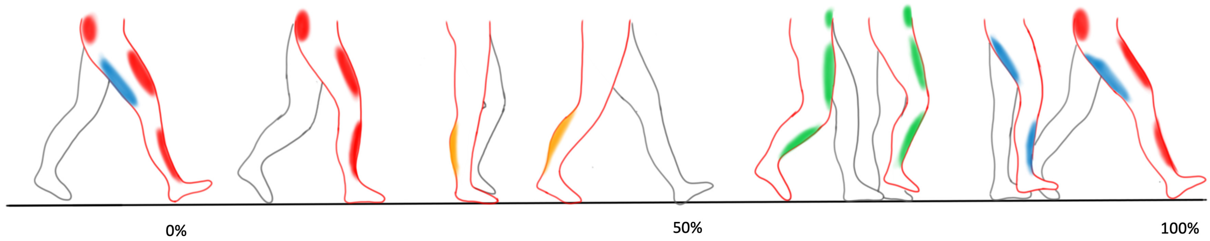

Loading Response	Mid-Stance	Terminal Stance	Pre-Swing	Initial Swing	Mid-Swing	Terminal Swing
Synergy A: Weight Acceptance		Synergy B: Forward Propulsion		Synergy C: Lift and Accelerate		Synergy D: Decelerate
Stance				Swing		

Figure 2. Key phases and active muscle synergies during the gait cycle.

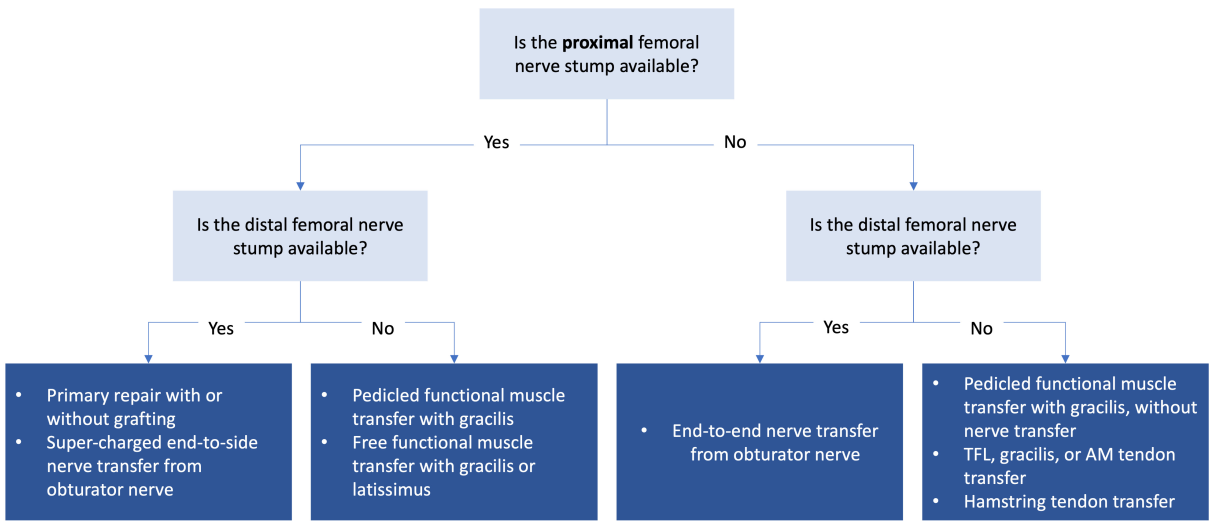

Figure 3. Reconstruction algorithm for complete femoral nerve injuries.

vastus lateralis, primarily [Figure 4]. Variations in number of donor and recipient branches, sub-muscular *vs.* supra-muscular tunneling over the adductor longus, and use of contralateral obturator nerve have been described[32,33]. While other potential donor nerves, such as the nerve to the tensor fascia lata (TFL) and the sciatic nerve can be considered when the obturator nerve is not available, our experience supports the obturator nerve as a reliable donor for achieving functional knee stability and extension and negligible donor morbidity.

In the absence of recipient nerves for transfers to the quadriceps muscles either due to muscular injury, resection, or delayed presentation, tendon or muscle transfers must be used to recruit a new neuromuscular unit for knee extension. If proximal femoral nerve fibers are available to neurotize a functional muscle transfer and intuitive control without the need for cortical re-education, then local or free functional muscle transfers can be used to restore intuitive knee extension. The latissimus dorsi muscle has been described in multiple reports as a viable option for functional free muscle transfer, with modest results that depended on the degree of quadriceps extirpation[34,35]. In patients who lost all four quadriceps muscles, knee extension improved from 0/5 immediately post-op to 2 or 3/5 after reinnervation of the latissimus; in patients who lost three quadriceps muscles, strength improved from 2/5 to 4/5 with reinnervation[35]. In our opinion, the pedicled gracilis is the most practical and high-yield option for functional muscle transfer. As described by

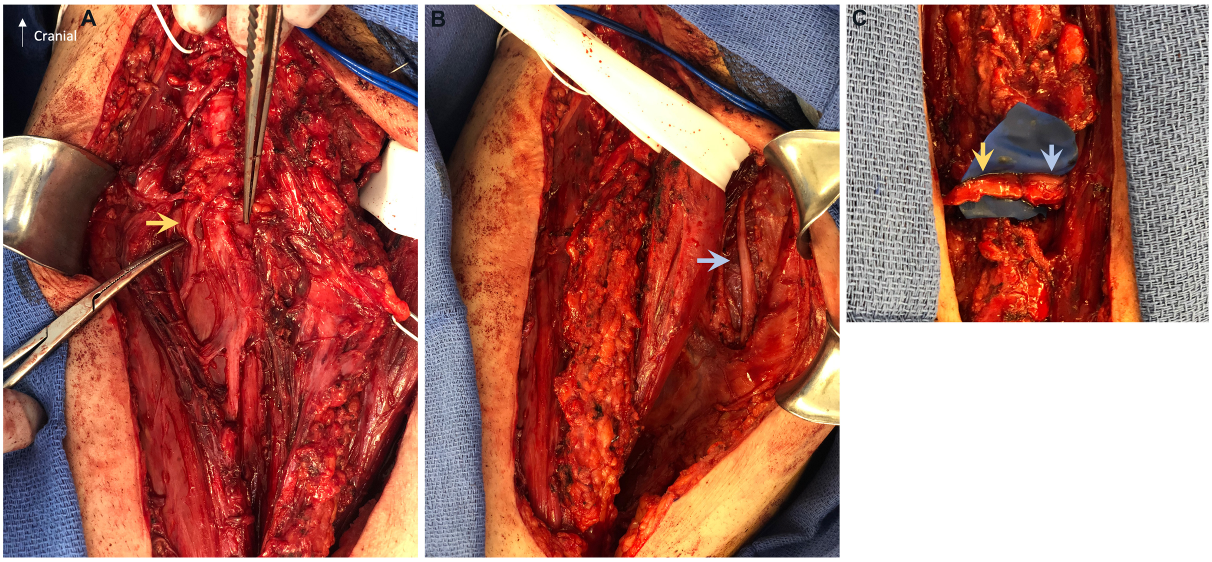

Figure 4. Obturator to femoral nerve transfer. This patient suffered a high right femoral nerve lesion from a groin mass excision. Identification of a caliber-matched branch of the femoral nerve (yellow arrow) going to the rectus femoris and vastus lateralis (A) through an anterior approach. Identification of the branch of the obturator nerve (blue arrow) going to the gracilis (B). Coaptation of the obturator nerve to the femoral nerve (C). This patient achieved MRC grade 4 knee extension. MRC: Medical Research Council.

Nguyen *et al.*[36] in 2019, the ipsilateral gracilis can be freed and tunneled to the anterior compartment on its pedicle, then secured in position to replace the function of the rectus femoris. Any available femoral nerve fibers are coapted to the nerve to the gracilis, whose length can be adjusted based on the length of available femoral nerve fibers (in the case of complete femoral nerve injury, the nerve to the gracilis can be left intact). Nguyen *et al.*[36] report that all 3 patients with long-term follow up achieved MRC grade 4 knee extension with appropriate exercise and training. Although this will not provide enough strength for forceful push-off to climb stairs or rise from sitting, it may be enough to provide knee stability to enable walking with or without a cane. Because of the straightforwardness of the surgical technique, avoidance of microvascular anastomosis, minimal donor site morbidity, and potential for good functional outcomes, we opt for the gracilis functional muscle transfer when available.

In the case of complete femoral nerve injury, tendon or muscle transfers without nerve transfer can be performed. Several donor tendons have been described, including hamstring transfers, adductor transfers, gracilis tendon transfers, and TFL transfers[37,38]. Fischer *et al.*[37] describe a larger series of 17 patients who underwent sole biceps transfer or other combined biceps/semitendinosus/gracilis transfers for quadriceps restoration. Extension and flexion forces were only 44% and 74%, respectively, of the unaffected leg, likely limited by the antagonism between the hamstring muscles and the quadriceps muscles they are attempting to replace. However, most of their patients (59%) did not rely on assistive walking devices, which speaks to the knee stability that these antagonistic transfers provide during the early stance phase. Alternatively, transfers of the TFL or medial compartment muscles may be more synergistic and lend themselves to more intuitive rehabilitation. The TFL offers many benefits, including straightforward dissection, ample tendon length, and favorable vector, but its excursion is limited[38,39]. Medial compartment donors include the gracilis or adductor magnus, which can be combined with TFL transfers[40].

The degree of functional recovery for femoral nerve reconstruction will depend heavily on the degree of the defect. For extirpations of three or four quadriceps muscles, it is unreasonable to expect recovery of full strength in any single reconstructive maneuver. Depending on the patient's desired functional recovery, combinations of tendon transfers may be required to optimize strength, knee stability, and function. For example, free functional muscle transfers may be augmented with medial compartment tendon transfers. Investigations into outcomes for these tendon transfers are ongoing.

Reconstruction of sciatic nerve injuries

Sciatic nerve injuries carry a poor prognosis and are almost always associated with chronic disability, particularly in the adult and elderly populations. Incomplete lesions or injuries due to compression fare better than complete lesions, and distal injuries fare better than proximal injuries[41]. If the nerve is in continuity, exploration and neurolysis can have good results. However, it is not uncommon for a neuroma-in-continuity to be present. In those cases, if there are no nerve action potentials crossing the neuroma, then excision and fascicular repair of the tibial and peroneal components of the nerve are indicated. Generally, the CPN component of the sciatic nerve is more prone to injury due to its lateral position and decreased elastic tolerance owing to its double point of fixation at the greater sciatic notch and fibrous tunnel around the knee. The tibial nerve, on the other hand, is more elastic, has better blood supply, and has more perineural connective tissue, which is thought to help protect its axons. As observed in a large series of 806 sciatic nerve injuries, outcomes appear to be better for tibial nerve repair than CPN repair for both primary coaptation and secondary grafting[42].

For high sciatic nerve injuries where nerve regeneration to the posterior compartment of the lower leg is unlikely, early nerve transfers are indicated [Figure 5]. Reconstruction of the tibial nerve is generally prioritized over CPN reconstruction, because of its important role in balance during gait and the availability of alternative strategies for managing CPN palsy (e.g., orthoses). The goal of reconstruction is then to restore forceful plantarflexion. Yin *et al.*[43] report a series of 5 patients with sacral plexus injuries in which they transferred the ipsilateral obturator nerve to the branch of the tibial nerve innervating the medial head of the gastrocnemius to restore knee flexion and ankle plantarflexion. Three of five patients achieved MRC grade 3 or better. Moore *et al.*[44] report two patients in which femoral to tibial nerve transfers were performed for high sciatic nerve injuries. In the first patient, the nerve to the vastus medialis was transferred to the nerve to the medial head of the gastrocnemius with an interpositional peroneal nerve graft. In the second patient, the same transfer was performed, except with direct coaptation, and a concomitant transfer of the branch to the vastus lateralis to the lateral gastrocnemius was performed. Both patients achieved MRC grade 3 plantarflexion by 18 months. The peroneal nerves were not reconstructed in these two patients.

With respect to the normal gait cycle, the femoral and tibial nerves activate sequentially: the quadriceps are active just before heel strike throughout early stance, after which the plantar flexors activate to provide some forward propulsion and, more importantly, to stabilize the ankle as it dorsiflexes through mid- to late-state[45]. Because of their sequential roles in the gait cycle, femoral to tibial nerve transfer may be a reasonable option to rehabilitate. Alternatively, the obturator nerve branches to the gracilis play little role in the gait cycle, making them attractive, expendable options for transfer. The obturator nerve is our preferred donor for motor restoration of the tibial nerve in a sciatic nerve injury.

To prevent long-term complications from chronic injury, the sensory deficit of the plantar foot is the most important tibial nerve function to restore. This will be discussed in the section below on reconstructing tibial nerve injury.

Reconstruction of isolated common peroneal nerve injuries

Owing to its superficial position at the fibular neck and inability, injuries to the CPN are the most frequent among the lower extremity nerves. These are associated with knee trauma and iatrogenic injury, usually

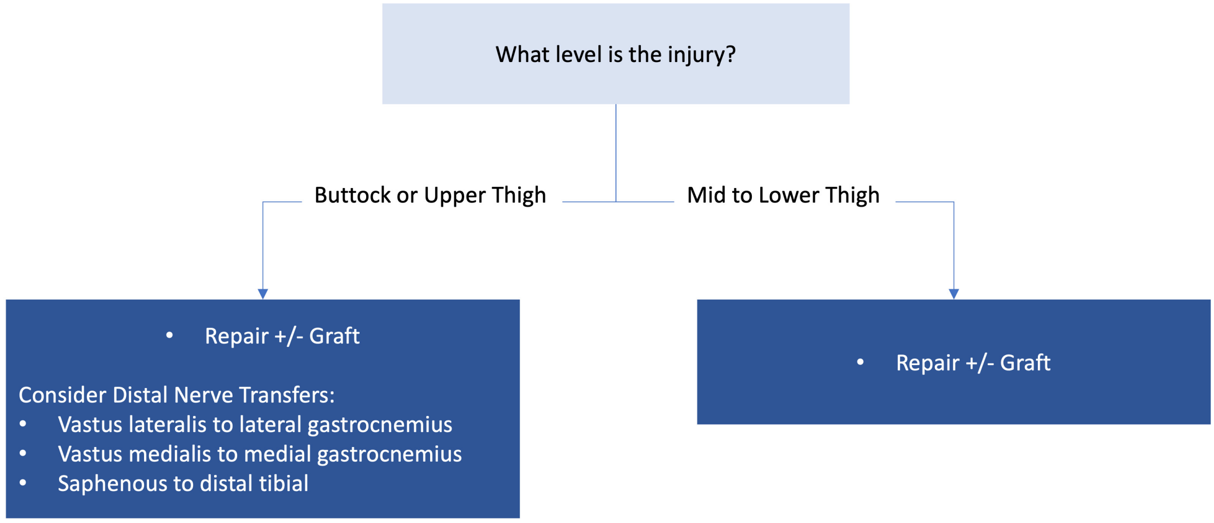

Figure 5. Reconstruction algorithm for complete sciatic nerve injuries.

from surgical positioning or orthopedic procedures of the knee. Injury to the CPN results in characteristic foot drop and sensory deficits of the dorsal foot. Untreated, this results in a varus deformity and steppage or foot-slapping gait.

For axonotmetic injuries (Sunderland II-IV), based on the clinician's cumulative assessment of the history, exam, electrodiagnostic and imaging findings, the rate of full spontaneous recovery ranges from 76% to 87%. However, in cases where spontaneous improvement is not evident after four months or if complete injury is suspected, surgical intervention is indicated [Figure 6][46,47]. In a review of 1577 CPN repairs, George and Boyce[48] reported that good outcomes, defined as MRC 4 or better, were observed in just 45% of cases. Outcomes were better in injuries that only required neurolysis (80% good outcomes), namely entrapment or compression injuries. Individual reports of CPN injuries requiring end-to-end repair or interpositional grafting (lacerations or stretch-avulsion injuries) have claimed as high as 84% good outcomes, but the literature aggregate is only 37%[41]. A criticism of this study is that method of management is confounded by the mechanism and severity of injury, and criteria for choice of management are not clear. In general, we posit that the mechanism and severity of injury are major determinants of outcomes; clean lacerations and compression injuries tend to do well (60%-85% good outcomes), while traction and high-energy trauma fare poorly (30%-50% good outcomes). The length of nerve graft is also a major determinant of outcomes, with the percentage of patients achieving good outcomes decreasing to 29% from 64% grafts exceeded 6 cm[48]. Few surgeon-modifiable levers are available other than expediting time to intervention.

Some have hypothesized that vascular insufficiency is a limitation to conventional nerve grafts for CPN reconstruction, so vascularized nerve grafts have been attempted. Terzis and Kostopoulos[49] performed 12 vascularized nerve grafts (medial and lateral sural nerves) for CPN defects ranging from 4 to 18 cm gaps. An impressive two-thirds of their patients with graft length greater than 13 cm demonstrated dorsiflexion against gravity, but they lacked a comparison cohort of patients with conventional grafts. Furthermore, the vascularized nerve grafts shorter than 13 cm actually performed worse than the comparator set of conventional grafts. A recent review of vascularized nerve grafts concludes that there is evidence suggesting better blood supply and enhanced nerve regeneration, but there are few clinical scenarios where that difference is meaningful[50]. No studies demonstrate compelling evidence for their superiority over conventional grafts. For these reasons as well as the added complexity of the procedure, vascularized nerve

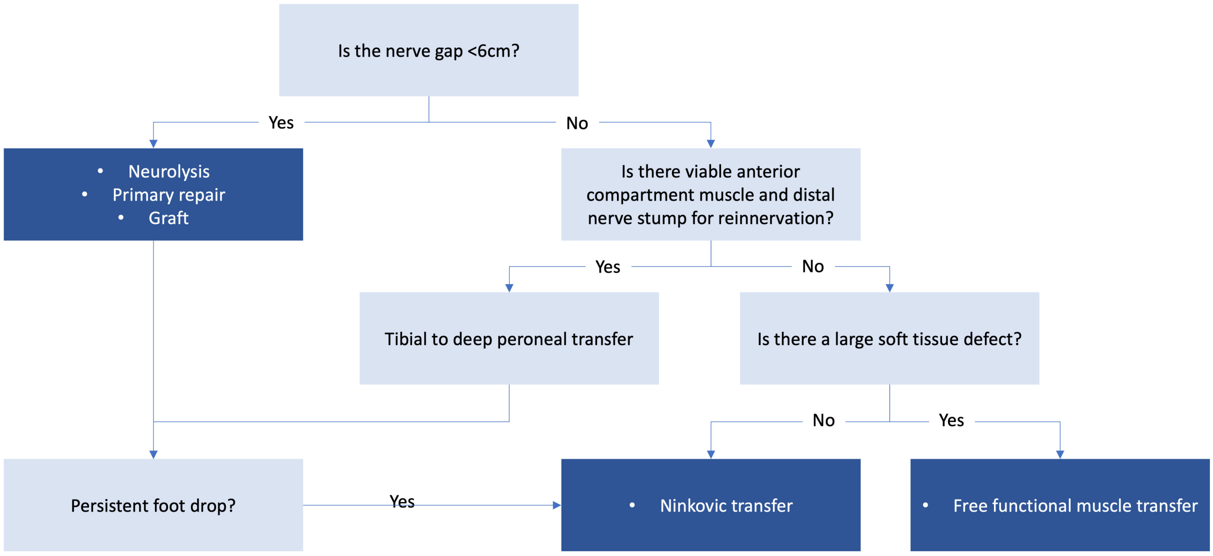

Figure 6. Reconstruction algorithm for complete common peroneal nerve injuries.

grafts are not currently a part of our treatment algorithm in functional lower extremity reconstruction.

When repair of the peroneal nerve is not feasible with a short conventional graft (less than 6 cm) then nerve transfers or tendon transfers should be considered [Figure 3]. When viable anterior compartment muscles and distal nerve stumps are available, tibial to deep peroneal nerve transfers can be performed. Leclere *et al.*[51] describe their experience in six patients, of whom, half gained MRC grade 4 strength or better. Another series of soleus branch to deep peroneal nerve transfers demonstrated MRC grade 4 strength in two of six patients, with the remaining patients having grade 2 or worse[52]. In general, the reliability of these nerve transfers appears poor compared to tendon transfers. A major concern is the difficulty in achieving cortical integration with a purely antagonistic transfer in which a nerve supplying an ankle plantar flexor is used to restore dorsiflexion. Transfers of the nerves to flexor hallucis longus and flexor digitorum longus may be easier to rehabilitate, but the reliability of these transfers is sensitive to patient age and time of surgery[53,54].

For persistent CPN palsy, tendon transfers can help restore dorsiflexion at the ankle. Traditionally, variations of posterior tibialis tendon transfers are employed, either circumtibial (Ober transfer), interosseous (Watkins transfer), or as a bridle through the anterior tibialis and peroneus longus (Riordan transfer or Bridle procedure)[55-59]. While the Bridle procedure does help improve dorsiflexion and is associated with good subjective outcomes, these transfers have poor synergism and tend to be stiff. Cho *et al.*[60] followed 17 Bridle procedure patients who reported improved subjective outcomes but worse kinematic measures than controls. Similarly, Johnson *et al.*[61] followed 19 Bridle procedure patients and identified worse outcomes in several specific measures, such as the Foot and Ankle Ability Measure subscales of activities of daily living and sport, single-limb standing-balance reach test, and dorsiflexion/plantarflexion range of motion *vs.* controls. Interestingly, despite poor functional scores, all Bridle procedure patients reported good to excellent satisfaction and were able to avoid the use of an ankle-foot orthotic for daily everyday activities. In total, it seems that the benefit of the Bridle procedure is to essentially form an internal splint to help maintain the ankle in a dorsiflexed position which enables orthotic-independent gait, but falls short of providing the functional benefits typically expected of tendon transfers.

An emerging technique is the Ninkovic transfer, which entails a neurotized transfer of the gastrocnemius to the anterior compartment of the leg [Figure 7][62]. This requires the availability of a proximal peroneal nerve stump, which is transferred to the tibial branch to the lateral gastrocnemius[63]. The lateral gastrocnemius tendon is then transferred and attached to the anterior tibialis. After reinnervation of the gastrocnemius with the peroneal nerve, intuitive dorsiflexion with full excursion of the ankle can be obtained. Unlike posterior tibialis transfers, this provides better muscle balance, synergism, and avoidance of hind foot valgus deformity and flat foot deformity associated with sacrificing the tibialis posterior. Since its original description, multiple variations have been described, such as transfer of the medial gastrocnemius to the anterior compartment (the medial head provides greater muscular excursion than the lateral head of the gastrocnemius) with or without transfer of the lateral gastrocnemius to the lateral compartment under its native tibial innervation[63,64]. In Ninkovic's largest series of 18 patients, nine underwent medial gastrocnemius transfer, seven underwent lateral head transfer, and two underwent both. All patients achieved full range of motion within 18 months and all walked without an ankle-foot orthosis. While its outcomes require ongoing study with direct comparisons to other reconstructive options, the Ninkovic transfer is currently our preferred method for surgical management of persistent foot drop.

Free functioning muscle transfers are another option for peroneal nerve and anterior compartment deficits[65]. Reliable options include gracilis and rectus femoris flaps, which can be taken with skin paddles. Reinnervation can be achieved with peroneal or tibial branches, depending on what is available. Lin *et al.*[66] report on 17 patients with complex lower extremity defects who underwent anterior compartment reconstruction with gracilis or rectus femoris flaps. All patients achieved independence from orthoses, and 10 patients achieved good or excellent functional outcomes by Stanmore criteria. Ultimately, we reserve these for large composite defects of the leg that involve the posterior compartment or require significant soft tissue coverage.

Reconstruction of tibial nerve injuries

Isolated injuries of the tibial nerve are rare, with traumatic and iatrogenic injuries occurring 2-3× less frequently than CPN injuries[2,5,42]. However, the motor and sensory deficit associated with tibial nerve injury can be very morbid. Although the tibial nerve is not critical to gait, it contributes to gait efficiency; paralysis causes significant shortening of the contralateral step due to the inability to balance on the stance foot as the center of gravity moves forward [Figure 2][67]. Loss of protective sensation predisposes the patient to injuries and chronic wounds, and as such, restoration of protective sensation is an important goal of tibial nerve reconstruction [Figure 8].

In most cases, primary neurorrhaphy or grafting can provide satisfactory results [Figure 9]. As reported by Murovic[42] and Kim *et al.*[68] in a large series of lower extremity peripheral nerve trauma patients, outcomes for nerve repair were better at the knee-to-leg level for the tibial nerve than for all other nerves and injury levels. Primary suture or graft repair of the tibial nerve yielded 100% and 94% "good" or better outcomes, respectively, indicating MRC grade 3 or better plantar flexion with intact light touch sensation. The success of tibial nerve repair was attributed to the short regeneration distances to the calf muscles and the nerve's robust blood supply. It appears that outcomes are not affected by graft length up to 12 cm, but there is little data to draw conclusions about graft length in tibial nerve repairs[68,69]. Interestingly, outcomes of tibial nerve repair at the ankle were worse, yielding only 64% good outcomes. This was attributed to the tendency for ankle-level injuries to be related to traction injuries propagated over a large distance which required excision and long grafts. Nonetheless, repair of the tibial nerve should always be attempted even in very delayed cases with large nerve gaps, as sensory recovery can be achieved even after complete loss of muscle motor endplates occurs.

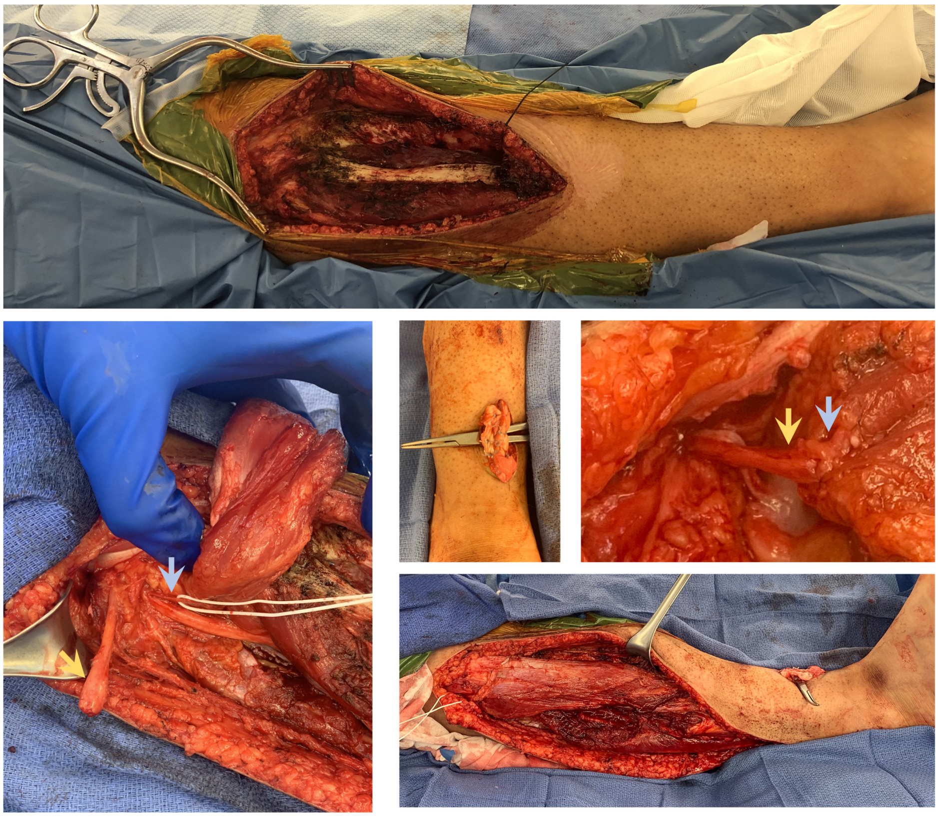

Figure 7. Ninkovic transfer. This patient underwent sarcoma resection in the right lower extremity, which resulted in obliteration of the proximal anterior and lateral compartment of the leg, including the terminal branches of the deep peroneal nerve (Panel 1). A Ninkovic transfer was performed, starting with disinsertion and elevation of the lateral gastrocnemius while maintaining its tibial innervation (blue arrow, Panel 2). The injured common peroneal nerve is identified (yellow arrow, Panel 2). The lateral gastrocnemius tendon is then transferred to the tibialis anterior, extensor digitorum longus, and extensor hallicis longus tendons (Panel 3). Finally, the deep peroneal nerve (yellow arrow) is transferred to the nerve to the lateral gastrocnemius (blue arrow, Panel 4). In this case, the anterior transposition of the lateral gastrocnemius adequately covered the soft tissue defect over the bone (Panel 5).

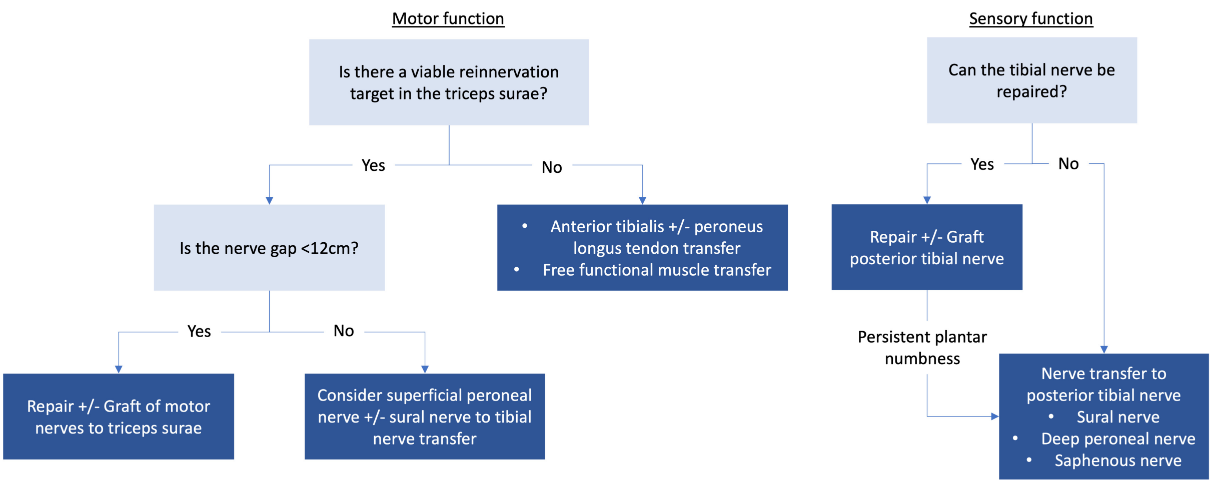

Figure 8. Reconstruction of tibial nerve injuries for motor and sensory restoration.

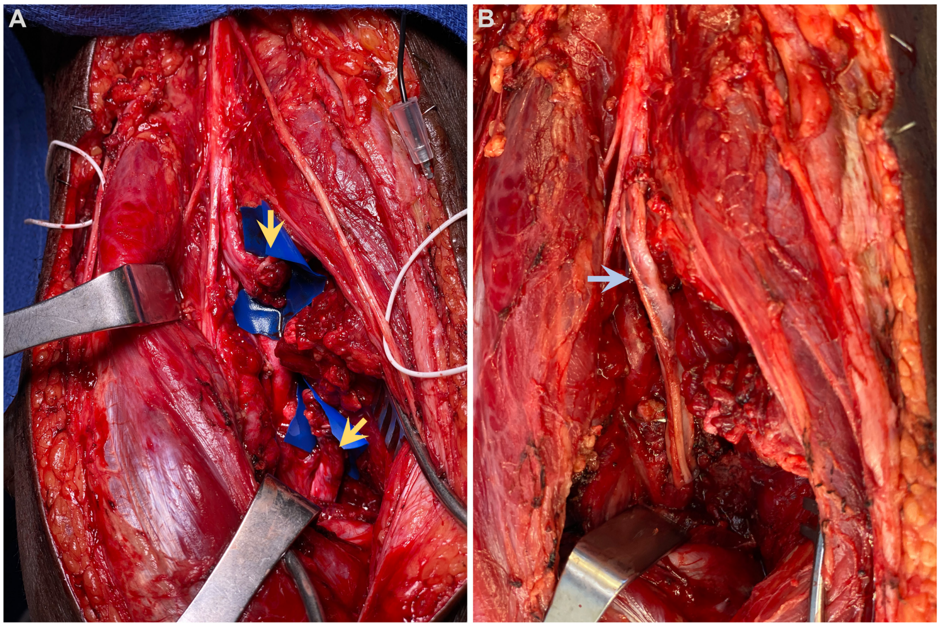

Figure 9. Tibial nerve repair by sural cable graft. This patient suffered a gunshot wound in the leg resulting in transection of the tibial nerve. Proximal and distal stumps (yellow arrows) are identified (A). The proximal and distal stumps were breadloafed back to healthy-appearing fascicles and an interpositional sural cable graft (blue arrow) was used to repair the resulting defect (B).

For persistent plantar anesthesia, sensory nerve transfers to the tibial nerve are viable options [Figure 8]. The transfer of the distal sensory branch of the deep peroneal nerve has been reported in two patients[70]. A double transfer of the superficial peroneal and sural nerves has been described in an anatomic feasibility study, but has yet to be reported in patients[71]. Saphenous to tibial nerve transfer has been described in two reports with promising results, including one study in diabetic neuropathy in which all diabetic ulcers healed after saphenous transfer[72,73]. In total, repair of the tibial nerve proper should be attempted given its generally good outcomes even with long regenerative distances. However, in the case of persistent loss of plantar sensation, novel nerve transfers should be considered based on the availability of donor nerves.

If repair of the tibial nerve cannot restore motor function, tendon transfers or free functional muscle transfers can be used, but the literature experience is scant. The tibialis anterior with or without peroneus longus can be transferred to the calcaneus[74]. The neurotized rectus femoris free flap, with or without a skin paddle, has been described in two cases for the reconstruction of the posterior compartment[66,75].

CONCLUSIONS

Nerve reconstruction has made major strides in the past several decades. The advent of multidisciplinary limb-salvage teams, enhanced microsurgery and nerve repair techniques, and creative nerve and tendon transfer schemas have allowed for considerable improvements in pain and functional restoration. In this growing and ever-evolving field, it is essential for reconstructive surgeons to understand the principles and outcomes behind these innovative procedures.

Recognition and accurate diagnosis of nerve injuries are among the most important modifiable factors for surgical outcomes. This relies on a thorough history, physical exam, and appropriate use of electrodiagnostics and imaging. Still, many nerve injuries are under-recognized by non-specialists. Due to incomplete understanding of nerve pathophysiology, the pain and weakness resulting from peripheral nerve axonotmesis can often be incorrectly attributed to neuropraxia or some other cause. Patients may end up pursuing months of observation or other therapy while the window of opportunity to achieve reinnervation narrows. In general, awareness of PNIs and reconstructive options is low, and we suspect many patients and their providers are unaware of the options available to them.

Ultimately, our ability to achieve optimal outcomes is limited by anatomical and physiological parameters. Tibial and femoral nerve injuries tend to fare well, but sciatic and common peroneal nerve injuries - which comprise the majority of lower extremity PNIs - have worse results. In fact, segmental CPN injuries have such poor regenerative potential that some centers opt for the Bridle procedure in lieu of nerve repair. Continued innovation in novel nerve and tendon transfer techniques, as well as basic science research in nerve physiology and regeneration will continue to expand treatment options.

One novel strategy under active investigation is the utility of nerve elongation. Based on the observation that segmental nerve defects requiring cable grafts tend to fare worse than injuries that can be repaired by primary coaptation, the goal of this strategy is to shorten the nerve gap so that primary repair can be achieved. For example, knee flexion can facilitate primary coaptation of a segmental CPN defect, and progressive extension of the knee over several weeks can allow for elongation of the nerve so that full range of motion can be achieved[76]. Another example would be in the setting of a thigh-level sciatic nerve injury, in which a femoral shortening osteotomy can bring the nerve stumps together for primary repair, and then femor length can be later restored with distraction osteogenesis. Such clinical experiences are anecdotal and sparsely reported in the literature, but there is growing pre-clinical evidence demonstrating that stretch forces play an important role in axon elongation and orientation[76-79]. More clinical data is needed to assess the relative risks and benefits of such strategies against cable grafting.

Other areas of future research should include continued accrual of patient outcome data and comparative assessments between interventions for complex reconstructions. By nature of the infrequency and heterogeneity of PNIs, outcomes data for any given procedure is almost universally based on small case series. Success of motor reconstruction can be measured in terms of strength and range of motion across a joint in isolation, but to facilitate comparison between interventions it is more meaningful to measure the performance of compound motions such as assisted *vs.* unassisted gait, walking on inclined surfaces, and ability to sit or stand. Continued study of muscular synergies during gait will also help contextualize reconstructive options as they pertain to restoring functional gait [Figure 2].

In summary, many options have been described for PNIs of variable severity and location, and patients with what were previously thought to be highly morbid injuries stand to benefit from advanced reconstruction. Therefore, it is important for orthopedic and plastic surgeons to be aware of the diagnosis, prognosis, and available reconstructive options for PNIs so that the correct interventions or referrals can be made in a timely manner.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception of the article, writing, and editing: Qiu CS, Hanwright PJ, Khavanin N, Tuffaha S

Performed the cases provided clinical images presented in the article: Tuffaha S

Designed and illustrated figures: Qiu CS

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All authors declare that there is no conflict of interest.

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Not applicable.

Consent for publication
All subjects consented to capture and publication of photographs for research.

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