

Review

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Lower extremity nerve transfers: an under-appreciated reconstructive approach

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Abstract

Lower extremity peripheral nerve injuries can be highly morbid to patients and challenging problems for reconstructive surgeons to manage. Nerve transfers have recently emerged as a promising technique in the treatment of these injuries. The nerve-transfer paradigm is predicated on the use of an expendable, unaffected nerve as a donor of axons to restore motor or sensory function in the target end organ. Distal transfers close to the end motor or sensory organ may allow for earlier and more robust reinnervation compared to more proximal primary repair or grafting. However, as clinical data on outcomes and rigorous comparative studies remain scarce, reconstructive surgeons must rely on principle-based treatment including a detailed understanding of lower extremity neuromuscular anatomy, gait mechanics, and nerve physiology to develop an appropriate treatment plan for each patient with the goal of functional limb restoration and independent gait. In this article, we review current concepts of lower extremity nerve transfers, including techniques and outcomes according to indication.

Keywords: Lower extremity nerve injury, nerve transfer, peripheral nerve surgery



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INTRODUCTION

Peripheral nerve injury is a debilitating form of trauma that can have a lifelong impact. The paradigms for managing these injuries have evolved over time from the use of tendon transfers to early exploration, neurolysis, and primary repair, to nerve grafting. Nerve transfers have gained popularity in recent decades and are now considered an integral part of nerve injury management. The reconstructive plan must be tailored to each individual case and can often involve some combination of different techniques.

Nerve transfers are predicated on the use of an expendable, unaffected nerve as a donor of axons to restore motor or sensory function in the target end organ. Anatomic proximity, size match, and number of donor fascicles all influence the choice of donor nerves. For motor nerve transfers, the transfer of motor fascicles that control synergistic movements rather than antagonistic movements to the recipient is preferred, although not required. This strategy allows for more facile motor relearning and accelerated postoperative rehabilitation. Nerve transfers also allow surgeons to work outside the zone of injury and directly coapt nerve ends without the need for nerve grafting. Nerve transfer closer to the end motor or sensory organ allows for earlier reinnervation than a more proximal primary repair or grafting and can result in the transfer of more axons by avoiding the inevitable axonal loss associated with multiple coaptations and long grafts. Surgeons should be mindful of the risk of donor site morbidity and be strategic in their choice of a donor so that backup options, such as tendon transfers, are still available if the nerve transfer should fail.

Historically, peripheral nerve injury research has focused more on the upper rather than the lower extremity. However, lower extremity paralysis and sensory loss remain significant causes of disability and decreased quality of life. Independent ambulation and efficient gait result from different lower extremity muscles working in concert. Muscle weakness or paralysis due to neuropathy can negatively affect gait mechanics and increase the work of ambulation, if not making it impossible. Lower extremity nerve injury, like that in the upper extremity, has various etiologies-trauma, iatrogenesis, compression or entrapment, or systemic medical conditions. The site of the lesion can occur anywhere along the course of the neuron.

Studies of large trauma databases have shown that about 1%-2% of patients with lower extremity trauma had concomitant peripheral nerve injuries^[1,2]. In one study analyzing the National Inpatient Sample (NIS) database, the mean incidence of lower extremity peripheral nerve injuries was 13.3 cases per million population per year^[3]. The incidence of lower extremity peripheral nerve injuries is lower than that of the upper extremity^[3], which may be due to the overall protected location of lower extremity nerves, such as in the pelvis and when coursing deep to the thick musculature of the thigh and leg. When patients with lower extremity trauma with associated peripheral nerve injuries were compared with patients with lower extremity trauma without nerve injury, there were a greater proportion of patients who had sustained trauma due to motorcycle collisions^[1]. Several studies suggest that the relative risk to a specific nerve depends principally on the etiology and mechanism of injury^[1,3,4]. Another NIS study, as well as a study of 270 patients with lower extremity peripheral nerve injury, showed that the most frequently injured nerve was the fibular nerve^[3,5].

This article will review current concepts and published literature pertaining to lower extremity nerve transfers according to indication. Most of the current evidence regarding lower extremity nerve transfers is comprised of case reports and case series, which highlights the need for larger, more rigorous studies. In addition, readers should be aware of the risk of publication bias when interpreting results.

LUMBOSACRAL PLEXOPATHY

The lumbosacral plexus is comprised of the anterior rami of the L1 to S4 nerve roots. The lumbar plexus (L1 through L4) forms the iliohypogastric, ilioinguinal, genitofemoral, lateral femoral cutaneous, femoral, and obturator nerves. The lumbosacral trunk is formed by a portion of L4 and L5 and joins the anterior rami of S1 through S4 to form the sacral plexus. The sacral plexus forms the superior and inferior gluteal, posterior cutaneous, pudendal and sciatic nerves.

Injury to the lumbosacral plexus is rare but has been described as secondary to pelvic trauma and iatrogenic injury during pelvic or spinal surgery^[6-11]. The approach to these injuries should be similar to that for brachial plexus injuries. A detailed history and physical exam should be undertaken and repeated electromyography should be obtained to determine what nerve roots are affected, the possibility of recovery, and the location of the injury. Magnetic resonance imaging (MRI) is the preferred imaging modality for evaluating nerve root avulsions^[12]. Primary repair with or without nerve grafting can be successful at restoring proximal muscle function; however, given the distance to the distal lower extremity musculature, nerve regeneration is unlikely to reach the target motor endplates before muscle atrophy occurs^[7]. The intrapelvic course of the sacral plexus represents an additional challenge associated with primary repair. The peripheral nerve surgeon may, however, be consulted intra-operatively for immediate repair or reconstruction of an intrapelvic nerve that is sacrificed for an oncologic extirpation or is iatrogenically injured.

Likely owing to the rarity of these injuries, there are few clinical studies discussing surgical management of lumbosacral plexopathy, all of which are small case series^[7,13-15]. The majority of these reports describe primary repair with nerve grafting. In patients with lumbosacral plexus avulsions and no ipsilateral donor options, transfer of the contralateral S1 nerve root to the affected inferior gluteal nerve and hamstring branch of the sciatic nerve^[15] and contralateral obturator to the affected femoral nerve have been described^[14,16]. Lang *et al.* described the transfer of right femoral nerve fascicles to the superior gluteal and sciatic nerve using nerve grafts and the transfer of left 10th and 11th intercostal nerves to the left femoral nerve in a patient with simultaneous right sacral plexus root avulsions and left lumbar plexus root avulsions^[13]. The reported patient was able to stand and walk after 1.5 years. Although there is a paucity of clinical studies on nerve transfers in patients with lumbosacral plexopathy, there are transfers that have been described for the management of peripheral lower extremity nerve injuries that could be applied to lumbosacral plexus reconstruction.

FEMORAL NERVE PALSY

The femoral nerve is responsible for hip flexion, knee extension, and sensation of the anterior and medial thigh and medial leg and foot. Femoral nerve palsy can lead to impairment and disability. Patients with isolated femoral nerve palsy may be able to ambulate by compensation with the other muscle groups, but stairs, inclines, and standing from a sitting position can be more challenging^[17,18]. They may also have a higher risk of falls^[19].

Obturator donor

Nerve transfer to the femoral nerve using branches of the obturator, sciatic, and sartorius nerves has been described^[16,18,20-25]. Studies describe using nerve transfers in patients in whom it was not feasible to access the nerve proximal to the injury for primary repair or in whom a long nerve graft would be required for primary repair. The obturator nerve can be transferred to the femoral nerve at the level of the pelvis^[20,26]. A more distal obturator nerve transfer can be an attractive option as it avoids dissection in a potentially scarred and previously traumatized pelvis, allows only motor nerves to be transferred, and preserves some

innervation to the hip adductors. Transfer of the anterior obturator branch to the distal femoral nerve or select motor branches of the femoral nerve has been described^[18,21,26-28]. Good return of function has also been reported with transferring branches of the obturator nerve to the gracilis and adductor longus to the quadriceps branch of the femoral nerve^[29]. With obturator nerve transfers, patients have been reported to regain at least 3/5 Medical Research Council (MRC) grade knee extension strength, with some regaining 4 or 5/5 strength^[18,21,26-28]. In regards to donor morbidity, studies describe transient or limited thigh adduction weakness with no functional impairment following nerve transfer^[16,18,20,28-30].

Sartorius donor

McInnes *et al.* found that in partial femoral nerve palsy, the sartorius branch was often spared and a feasible option for transfer to the quadriceps nerve^[22]. They describe coapting the sartorius nerve in an end-to-side fashion to the quadriceps branch if there is some stimulation of the quadriceps muscles and transferring the sartorius and obturator branches in an end-to-end fashion to the quadriceps if there is no quadriceps muscle stimulation. All six of the patients they treated achieved MRC 4-/5 or greater. The senior authors published an updated series of 14 patients with femoral palsy who were treated with a combination of end-to-end and end-to-side transfers with the anterior branch of the obturator, sartorius, or both^[18]. They report restoration of strong quadriceps function with MRC 4 to 5 and subjective improvement in gait by patients with these techniques. The sartorius muscle is widely considered expendable and routinely utilized for reconstruction, so usage of the sartorius nerve as a donor does not carry significant morbidity.

Other donors

There are several case reports of sciatic nerve fascicle transfer for femoral nerve palsy reconstruction^[23-25,30]. In one report of two patients, redundant sciatic nerve fascicles for toe extension were identified and transferred to femoral quadriceps branches in addition to obturator to femoral transfers^[30]. Knee extension for one patient improved from MRC 0 preoperatively to MRC 3 by 2 years following surgery, allowing the patient to ambulate without a knee brace and ascend and descend stairs. Knee extension for the other patient improved to MRC 3 by 8 months postoperatively compared with MRC 2 preoperatively. There was no weakness observed in the donors. Sciatic to femoral nerve transfers and thoracoabdominal intercostal nerve transfer with nerve graft have also been performed in pediatric patients with acute flaccid myelitis who had involvement of the femoral nerve and obturator with sparing of the sciatic nerve^[23,24]. In one case series of 8 patients who underwent nerve transfers to address persistent lower extremity weakness following acute flaccid myelitis diagnosis, patients underwent varying combinations of nerve transfers using sartorius nerve (7 limbs), thoracoabdominal intercostal nerves (4 limbs), and sciatic nerve fascicles (2 limbs). Preoperative quadriceps strength ranged from MRC 0 to 2. Postoperatively, 6 limbs experienced an improvement in quadriceps strength, with postoperative MRC ranging from 2 to 4, and 2 limbs saw no improvement. One patient was lost to follow-up. Although large studies of these types of nerve transfers are lacking, the available data suggest that these are surgical options with minimal donor impact for patients with limited alternatives and significant functional impairment.

OBTURATOR

The obturator nerve innervates the muscles of hip adduction and provides sensation to the superomedial aspect of the thigh and to the knee and hip joints. The most common symptom of obturator neuropathy is groin or thigh pain^[31]. Injury to the obturator nerve is rare and the majority of patients are managed with conservative treatment, decompression, or primary repair with or without interposition nerve graft^[31,32]. Only one case report has been published of nerve transfer to the obturator^[33]. A patient sustained an obturator nerve injury following gynecologic resection of ovarian cancer and reported frequent tripping and inability to adduct the thigh. As the nerve injury was diagnosed 7 months following her initial surgery and she was likely to have extensive scarring in the pelvis, the authors chose to perform a femoral branch to

obturator nerve transfer rather than a primary repair. They identified a femoral nerve branch innervating the proximal quadriceps, which was a good size match to the obturator nerve. The patient was able to regain 5/5 strength in thigh adduction by 1 year following surgery and did not appear to have any donor morbidity, as she maintained full strength of knee extension.

SCIATIC NERVE PALSY

The sciatic nerve innervates muscles in the posterior component of the thigh, which perform knee flexion. At the level of the popliteal fossa, the nerve splits into the common fibular and tibial nerves, which are responsible for all motor functions of the ankle and toes. Branches of the common fibular and tibial nerves also provide sensation to the leg and almost the entirety of the foot, except the medial leg and medial foot which are innervated by the saphenous nerve, a branch of the femoral nerve. One of the most common etiologies of sciatic nerve injury is during total hip arthroplasty, in particular revisions or treatments for developmental hip dysplasia^[34]. Injury to the sciatic nerve can have many of the same signs and symptoms as fibular or tibial nerve injuries.

Only one case report has been published detailing nerve transfer for reconstruction of complete sciatic nerve palsy^[35]. The authors transferred the vastus medialis branch to the medial gastrocnemius in the first patient and two branches of the femoral nerve innervating the vastus medialis and vastus lateralis to the medial and lateral gastrocnemius branches of the tibial nerve, respectively, in the second patient. Both patients required interposition nerve grafts, but the vastus medialis to gastrocnemius transfer was able to be coapted directly. Additionally, the patients underwent staged sensory reconstruction, with the first stage transferring distal branches of the saphenous nerve to the sural nerve, followed by direct coaptation of the sural nerve to the tibial nerve at the ankle. The patients had a return of 3+/5 plantar flexion and improvement in gait mechanics. The authors report that the vastus motor nerve branches were the most suitable for transfer to the gastrocnemius branch, as the proximity can allow for direct coaptation when sufficient neurolysis was performed, as they learned in their second patient. The vastus and gastrocnemius muscle actions were also considered synergistic during ambulation as the quadriceps generate the most support during the foot-flat to contralateral toe-off phase and the ankle plantarflexors generate almost all the support during the late stance^[35,36]. No degradation of donor function was found in either of the patients.

In many instances, nerve transfers to address tibial or fibular nerve palsy can also be applied for sciatic nerve reconstruction.

TIBIAL NERVE PALSY

The tibial nerve innervates the muscles in the posterior compartment of the leg and intrinsic foot muscles. It contributes branches to form the sural nerve, which provides sensation to the posterolateral leg, and the tibial nerve is responsible for sensation on the plantar surface of the foot. The muscles controlled by the tibial nerve are responsible for propulsion by active ankle plantarflexion during gait and contribute to the stability of the ankle joint.

One systematic review and meta-analysis examined different treatments for tibial nerve injury^[37]. Of the 677 patients in the study, more than 50% of the patients underwent neurolysis, about 25% were treated with grafting, 13% with end-to-end repair, and 4%, or 30 patients, with nerve transfers. Four studies discussed nerve transfer: two were sensory nerve transfers to regain plantar sensation, one discussed anterior obturator to medial gastrocnemius transfer; and one described terminal femoral branches to gastrocnemius transfer^[35,38-40]. When the outcomes of motor nerve transfers were compared to other treatment modalities, the nerve transfers had the lowest mean MRC postoperatively and the proportion of patients who obtained

MRC was the lowest at 3 or higher (71%), but these patients had the longest mean preoperative interval and shortest follow-ups. A longer preoperative interval until nerve repair is known to be associated with poorer outcomes. The comparison of nerve transfers to other nerve injury treatments was also limited by the small sample size. As there are different indications for each treatment option, it may not be appropriate to directly compare outcomes from them due to confounding factors influencing the choice of procedure. The authors suggest that patients with proximal injuries, delayed decision to visit or surgical treatment, and/or long nerve gaps should be considered for nerve transfer. Patients with these injury characteristics are more likely to have poorer outcomes compared to those able to undergo early primary end-to-end repair of an injury close to the motor endplates.

Motor nerve transfers

Nerve transfer of the anterior branch of the obturator nerve to the medial gastrocnemius branch of the tibial nerve has been described in a case series of five patients with lumbosacral root avulsions who had intact femoral and obturator nerve function but no distal motor or sensory function. A long nerve graft was required for coaptation, and the mean length was 21 cm. Three patients obtained MRC 3 or greater of the gastrocnemius muscle and were able to ambulate independently. None of the patients were noted to have significant adductor muscle weakness. A case report of femoral nerve branches to vastus medialis and vastus lateralis transferred to gastrocnemius nerve branches for complete sciatic nerve palsy was discussed in the sciatic nerve section. There are no published reports of motor nerve transfers for injuries specifically of the tibial nerve, likely due to the short length of the tibial nerve to the gastrocnemius muscle making it more amenable to direct repair or repair with a short nerve graft.

Sensory nerve transfers

The loss of protective sensation of sole can lead to the development of ulcers, amputation, and falls^[41,42]. The superficial fibular nerve, deep fibular nerve, and saphenous nerve have been used as donors for nerve transfer with successful improvement in plantar foot sensation^[38,39,43,44]. In one study, 17 patients underwent saphenous to posterior tibial nerve transfer at the level of the tarsal tunnel and the majority had significant improvement in sensation with S3+ sensation on the MRC sensory grading scale. Koshima *et al.* transferred the deep fibular nerve to the medial plantar nerve at the level of the foot in two patients with improvement in plantar foot sensation at the expense of persistent sensory deficits at the heel^[39]. They report that the benefits of the procedure are rapid recovery given the distal surgical site, minimal donor morbidity, and simplicity of the surgical technique. The current evidence suggests that sensory nerve transfers are overall technically simple and have the potential to significantly benefit patients who have lost protective sensation on the foot plantar surface.

FIBULAR NERVE PALSY

Fibular nerve injury is the most common peripheral mononeuropathy of the lower extremity^[45], with a high incidence of injury during dislocation and fracture around the knee^[46,47]. The clinical entity of foot drop is the functional consequence of fibular nerve trauma, resulting in loss of ankle dorsiflexion and eversion. The result is a significant alteration of gait mechanics and a considerable impact on patient quality of life^[48,49]. Many closed injuries resulting in neuropraxia resolve in the weeks or months following injury. In these cases, nerve decompression at the fibular neck may accelerate recovery^[50]. Open injuries are associated with higher grades of nerve injury that are unlikely to resolve spontaneously. Although more distal deep-fibular transections are amenable to direct repair or nerve autografts, strength outcomes remain unsatisfactory in a considerable number of patients, particularly if a nerve gap exists^[51,52]. Restoration of gait in this context has traditionally included the use of an ankle-foot orthosis (AFO) and, in some cases, tendon transfer^[53,54].

Over the last decade, reinnervation of the fibular nerve and its distal branches by nerve transfer has been used successfully to manage foot drop^[55-61]. Similar to other nerve transfers in the lower extremity, there must be a balance between restoring ankle dorsiflexion (and decreasing reliance on an AFO) and minimizing donor site morbidity. Several donor nerves have been described to reinnervate the fibular-innervated musculature, specifically the tibialis anterior muscle. These include the tibial branches to soleus^[57,58,60] and gastrocnemius^[55,58], although their sacrifice may weaken “push off” strength during the gait cycle. The nerve supply to the fibularis brevis and longus muscles has also been described as a potentially more synergistic donor^[56]. Unfortunately, these nerves may not be suitable for transfer in instances of more proximal injury (i.e., partial sciatic or common fibular nerve injury). Partial tibial nerve transfers from branches of the flexor digitorum longus and flexor hallucis longus have also been reported, generally providing adequate length and little donor deficit^[55,61].

A recent review of outcomes after nerve transfer for foot drop showed a bimodal distribution of strength in the postoperative period, with most patients obtaining either MRC grade 0 or 4 strength^[62]. It has been suggested that to optimize outcomes, branches should be directly transferred to tibialis anterior to reduce the possibility of axons unintentionally reinnervating the toe extensors^[61]. Furthermore, there may also be utility in providing innervation to fibularis tertius in addition to tibialis anterior to provide additional dynamic ankle stability.

CONCLUSION

Lower extremity peripheral nerve injuries represent a unique challenge to the reconstructive surgeon. While most peripheral nerve surgeons are more experienced in the assessment and treatment of upper extremity nerve injuries, a similar approach incorporating serial physical exams, electrodiagnostic studies, and advanced imaging can lead to the successful application of familiar principles to achieve meaningful functional gains in lower-extremity nerve reconstruction. Just as when evaluating upper-extremity nerve injuries, the surgeon must take into account time since injury, the likelihood of spontaneous recovery, and distance from injury to motor targets, as well as available transfer options when treating lower-extremity nerve injuries. An appropriate treatment plan for a given patient may include a combination of direct nerve repair or reconstruction along with nerve and/or tendon transfers. Therefore, the reconstructive surgeon must also take care to avoid certain nerve transfers that could compromise tendon transfer options, such as posterior tibial tendon transfer for foot drop and adductor magnus transfer for knee extension^[54,63], and especially in patients presenting late or who otherwise have a low likelihood of successful functional restoration via nerve transfer. The risk of donor morbidity is another concern, although the selection of donor nerves with expendable function, or the use of function-sparing techniques such as fascicular transfer, may help mitigate this morbidity.

The application of functional nerve transfers to the lower extremity, as highlighted in this review, represents a promising additional treatment consideration alongside the more established techniques of nerve repair, nerve reconstruction, tendon transfers, and functional muscle transfers. However, robust clinical data to support the use of one transfer over another or nerve transfers over alternative reconstructive techniques are lacking, as the majority of the evidence thus far is limited to case series and susceptible to publication bias. Future studies incorporating prospective, comparative designs, ideally across multiple centers, will be required to better define indications for and outcomes from lower extremity nerve transfers. Until such data are available, reconstructive surgeons must rely on principle-based treatment including a detailed understanding of lower extremity neuromuscular anatomy, gait mechanics, and nerve physiology to develop an appropriate treatment plan for each patient^[64].

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Authors' contributions

Conceived of the study, drafted and revised the manuscript, and approved the final version: Yu JL, Crowe CS, Lipira AB, Sood RF

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