Neuromusculotendinous Transfer: An Original Surgical Concept for the Treatment of Drop Foot with Long-Term Follow-Up

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Background: An original surgical technique for the correction of drop foot is demonstrated.

Methods: Eighteen patients with drop foot underwent transfer of the lateral, medial, or both heads of the gastrocnemius muscle to the tendons of the anterior and/or lateral muscle group of the lower leg. The transferred muscle was reinnervated by nerve coaptation between the undamaged proximal part of the deep peroneal nerve and the motor branch of the tibial nerve supplying the gastrocnemius muscle.

Results: In all patients, the transferred gastrocnemius muscle showed signs of reinnervation within an average of 6 months after operation. Ten patients achieved excellent results, having regained stable, fully automatic walking without foot inversion/eversion and active range of foot movement of at least 40 degrees. Four patients achieved good results with active range of movement of less than 40 degrees but very stable functional gait. Satisfactory results were presented in three cases with stable ankle motion. Two of three cases had dual transfer of the gastrocnemius muscle and had a very stable ankle joint. In one fair case, the treatment improved stability and the patient was able to walk.

Conclusions: To compensate for the loss of function of the anterior muscle compartment, neuromusculotendinous transfer of the gastrocnemius muscle has proved to be highly successful. Voluntary movement of the transferred muscle and fully automatic walking was achieved in the majority of patients treated. In contrast to the commonly used treatment of tibialis posterior muscle transfer, no reeducation of the transferred muscle was needed. (*Plast. Reconstr. Surg.* 132: 438e, 2013.)

CLINICAL QUESTION/LEVEL OF EVIDENCE: Therapeutic, IV.

The muscles of the anterior and lateral compartments of the lower leg are innervated by the peroneal nerve and control eversion/inversion and dorsiflexion of the foot and toes. Peroneal nerve injury or muscle damage of the anterior compartment/lateral compartment causes muscular imbalance and drop foot. If the condition is not treated, secondary equinovarus deformities develop because of the uncompensated activity of the posterior muscle compartments. The current surgical treatment for drop foot deformity is tendon transfer of the tibial posterior muscle, sometimes combined with transfer of additional muscles of the posterior muscle compartments.[1,2]

In 1933, Ober[3] was the first author to describe a surgical technique for the treatment of drop foot, which used the transfer of the tibial posterior tendon around the medial border of the tibia to the dorsum of the foot. Watkins et al. improved this approach by transferring the tibial posterior tendon through the interosseous membrane.[4]

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Further improvements were the dual insertion of the tibial posterior tendon to balance the foot by Anderson[5,6] and Srinivasan et al.,[7] who split the tibial posterior tendon into two tails and inserted them into the tendons of the extensor hallucis longus and the extensor digitorum longus in the so-called tendon-to-tendon technique. Using tendons as distal attachment points helped to avoid foot deformities resulting from direct insertion into bone.[8] The most frequently used "bridle" transfer described by Riordan et al.[9] uses a tibial posterior tendon transfer through the interosseus membrane, with dual insertion into the tendons of the tibialis anterior and the rerouted peroneus longus muscle.[10–12]

Paradoxically, all of these procedures use the transfer of antagonistic plantar-flexing muscles of the posterior muscle compartments to restore dorsiflexion. Because the used muscle is still innervated by the tibial nerve and usually weaker compared with all the remaining muscles of the posterior muscle compartments, intensive reeducation and training are needed to increase strength and to achieve voluntary contraction.[11–13]

A gastrocnemius muscular transfer technique that completely overcomes limitations of tibial posterior muscle transfer was first described in 1994 by Ninković et al.[14] Complete dissection of the gastrocnemius muscle and subsequent transfer of the tendon to the tendons of the tibialis anterior, extensor hallucis longus, and extensor digitorum longus is combined with orthotopic reinnervation of the muscle by the undamaged proximal part of the deep peroneal nerve. This approach restores normal, fully automatic walking, and produces stability of the foot without being dependent on successful muscle reeducation. The purpose of this article is to present further surgical improvements, refinements of this technique, and results after long-term follow-up.

PATIENTS AND METHODS

All 18 patients were operated on by the first author (M.N.) in three institutions between May of 1989 and April of 2009. All patient data are listed in Table 1.

Patients were selected to undergo neuromusculotendinous transfer if they met the following five criteria:

1. Loss of muscle function in the anterior compartment or both anterior and lateral compartments of the lower leg related to irreversible posttraumatic paralysis of the peroneal nerve, or severe muscle defects in the anterior/lateral compartment of the lower leg, caused by compartment syndrome or tumor resection. Irreversible posttraumatic paralysis is defined by the lack of functional improvement and absence of reinnervation potential on electromyographic studies at least 18 months after injury, or the latest surgical intervention. However, patients with lesions at the myoneural junction or muscle loss were operated on earlier because they stood no chance of spontaneous nerve recovery.
2. Identification of a viable proximal part of the deep or common peroneal nerve was carried out clinically by the Tinel sign, ultrasound, magnetic resonance imaging, or intraoperatively. The lesion of the peroneal nerve had to be located distal to its branching from the tibial nerve.
3. Good passive joint movement with dorsal extension of the foot of at least 0 degrees.
4. Presence of normal muscles innervated by the tibial nerve.
5. Sufficient soft-tissue coverage in the region of tendon transfer (anterior distal third of the lower leg).[14]

Table 1. Patient Demographic Data

	Value
No. of patients	18
Sex	
Male	14
Female	4
Age, yr	
Mean	27
Range	12–62
Interval between nerve injury and neuromuscular transfer	
Mean	16 mo
Range	2 wk–5 yr
Cause of drop foot deformity	
Traumatic lesion of the peroneal nerve	7
Posttraumatic compartment syndrome	8
Sarcoma resection	2
Iatrogenic/intraoperative nerve lesion	1
Previous operations on the peroneal nerve*	13

*The average number of operations is 1.3 (range, 1–4).

Operative Technique

The operative procedure is carried out in three stages. First, the viable proximal part of the peroneal nerve has to be isolated and identified. In a bloodless field, an incision is made through the lateral popliteal region to isolate the deep branch of the peroneal nerve, a motor branch to the foot extensor musculature. Using an operating microscope, it is separated from the common

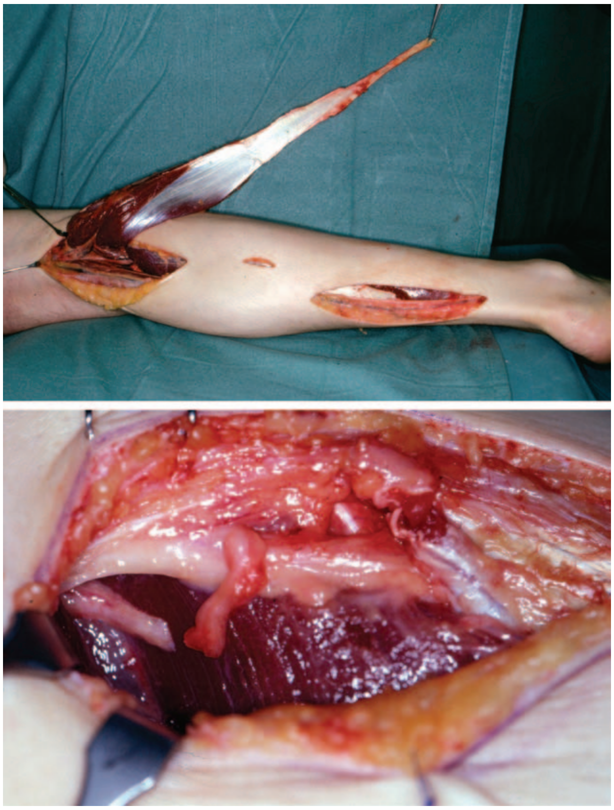

Fig. 1. (*Above*) Intraoperative view. Identification of a viable proximal part of the deep peroneal nerve with neuroma formation and a dissected motor branch of the gastrocnemius muscle with presented tibial nerve and the dissected lateral gastrocnemius muscle head with neurovascular pedicle and prepared for transfer to the anterior compartment. (*Below*) Intraoperative view. The deep peroneal nerve and motor branch of the gastrocnemius muscle are prepared for microsurgical suturing.

peroneal nerve and dissected until intact nerve fibers are exposed and sufficient length for tension-free nerve coaptation is obtained (Fig. 1). If the viability of the proximal stump of the peroneal nerve can be confirmed by means of the surgical view under the microscope and by histopathology, the operation can proceed.

The second stage starts with a skin incision at the posterior lower leg region, and a superficial part of the Achilles tendon is dissected and disconnected from the soleus muscle, together with the gastrocnemius muscle that is consecutively isolated until its origin and at the vascular pedicle to be transferred to the anterior side of the lower leg (Fig. 1, *above*). The tendons of the tibialis anterior, extensor digitorum longus, and extensor hallucis longus are prepared for suture through separate anterior incisions. Following this, the tendon of the transferred gastrocnemius muscle is sutured under maximal dorsiflexion of the foot to the tendons of the anterior compartment/lateral compartment. In the event of using only one gastrocnemius muscle, the maximal tension of the extensor digitorum longus tendon has to be applied to avoid foot inversion later. In a case of using both gastrocnemius muscles, the lateral gastrocnemius muscle head sutured to the peroneus brevis muscle keeps the foot in anatomical arrangement.

Now follows the final and most delicate third stage of the operation. The motor branch of the tibial nerve supplying the head of the gastrocnemius muscle and the deep branch of the peroneal nerve have to be carefully sutured under a microscope and without tension (Fig. 1, *below*). To allow quick reinnervation, the motor branch of the tibial nerve needs to be as short as possible. At the end of the operation, a padded above-knee plaster cast is applied to maintain maximal dorsiflexion of the foot.

The surgical procedure is identical for the transfer of the lateral (case 7) or the medial (case 9) head of the gastrocnemius muscle or both (case 2), except for the routing of the transferred tendon and their attachment points. In cases where the anterior compartment is restored, the tendon part of the medial gastrocnemius muscle head is transferred around the medial border of the tibia and attached to the tendons of the tibialis anterior, extensor digitorum longus, and extensor hallucis longus above the superior retinaculum extensorum. The same technique is used for the lateral gastrocnemius muscle head. However, in the case of using both gastrocnemius muscle heads, rebuilding the lateral compartment requires a transfer of the lateral gastrocnemius muscle head along the lateral border of the fibula to reach the tendon of the peroneus brevis muscle. In two cases, both heads were used and transferred as described above. The medial head of the gastrocnemius muscle received reinnervation by the peroneal nerve, and the innervation of the lateral head by the tibial nerve remained unchanged.

Rehabilitation

Immobilization remained for 6 weeks and was replaced by an ankle-foot orthosis in the neutral position, to prevent stretching of the muscle during reinnervation, followed by supportive physiotherapy treatment. The therapy included range-of-motion exercise and electrostimulation. Electrostimulation of the transplanted muscle began 6 weeks after the operation using a prescribed device, every day. In addition, the patients were instructed to work proactively during the passive-induced extension of the ankle joint. As soon as a voluntary muscle contraction grade 3 according to the Medical Research Council Scale had been achieved, the electrostimulation could be stopped. During the regular checkup, changes relating to range of motion were recorded.

RESULTS

At the time of follow-up (mean duration, 7.5 years; range, 2 to 25 years), all patients walked automatically without an ankle-foot orthosis and showed significant improvement of gait. No donor-site morbidity was noted. The average hospital stay was 8 days (range, 4 to 28 days). Primary wound healing was obtained in all but one patient. All patients were able to voluntarily contract the transferred muscle at an average of 6 months postoperatively. Full active range of motion was achieved within the first 18 months. Patient demographic data are listed in Table 1.

Electromyographic testing was regularly performed preoperatively, to confirm the absence of reinnervation potential, and postoperatively, to determine the reinnervation of the transferred gastrocnemius muscle. After 1-year follow-up, the outcome was assessed using dynamic electromyographic analysis (seven steps), not only to evaluate reinnervation and recovery of the transferred gastrocnemius muscle but also to document the synergistic dynamic motion between healthy tibialis anterior muscle and the transferred gastrocnemius muscle during gait analysis (Figs. 2 and 3). In addition, the degree of active range of motion (active range of motion of dorsiflexion/plantar flexion) was measured (Fig. 4). The data obtained classified our patients into one of the following four categories (Table 2):

Excellent results were achieved in 10 patients, four patients showed good results, satisfactory results were presented in three cases, and one patient had a poor result because of decreased muscle power and distal tendon adhesion. Two of three cases with dual transfer of the gastrocnemius muscle were in the satisfactory group. A third patient has a wound healing problem solved by means of a free fasciocutaneous scapular flap. Only one patient had fair results with unstable but improved gait and limited active range of motion of 20 degrees (Table 2).

One patient who had undergone gastrocnemius muscle transfer immediately after surgical débridement necessitated by compartment syndrome experienced skin necrosis of the distal third of his lower leg. Two revisions were necessary to close the defect by means of one local flap, and finally, one free scapular flap was necessary. Although electromyographic and clinical examination documented excellent muscle reinnervation and function, severe scarring and tendon adhesions explain the reduction of active range of motion to 25 degrees. As a result of this experience, two additional patients with compartment syndrome were operated on a second time after complete soft-tissue healing.

In our early patients (six cases), we transferred only the lateral head of the gastrocnemius muscle with the nerve coaptation to restore the anterior compartment. In two severe cases, complete damage and removal of the anterior and lateral compartments prompted the transfer of both gastrocnemius muscle heads. Transfer of the medial gastrocnemius muscle head replaced the missing function of the muscle of the anterior compartment and was performed according to the above-described technique. The lateral gastrocnemius muscle head was used for foot stabilization and substitution of lateral compartment but left under tibial nerve innervation. In both cases, the achieved balance of the foot was excellent. However, the active range of motion was reduced by approximately 25 degrees because of a tenodesis effect between the lateral head of the gastrocnemius muscle and the plantar flexors.

DISCUSSION

Tendon transfer of the tibial posterior muscle is currently the most frequently used method for surgical treatment of drop foot.[3,4,9,10,12] Although this procedure has had reasonable success in allowing patients to regain the ability to walk without assistive devices, the tibial posterior tendon transfer provides weak dorsiflexion and may not completely restore functional gait.[15]

We were determined to find a solution to four well-known problems related to this technique: first, tibial posterior transfer results in a significant disproportion of muscle force between the transferred tibial posterior muscle and the remaining plantar flexors.[12] Second, the simple transfer of the tibial posterior tendon does not allow voluntary dorsiflexion of the foot.[11,12,16] A successful tibial posterior transfer is dependent on active postoperative reeducation to decrease a functional antagonism between the transferred tibial posterior and the remaining muscles of the posterior compartment innervated by the same tibial nerve.[11,12,15,16] Third, tibial posterior transfer

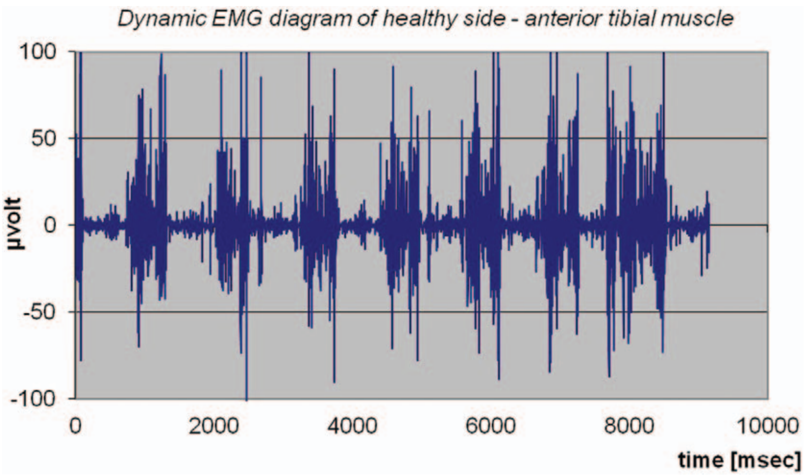

Fig. 2. Dynamic electromyography (*EMG*) during seven steps on the healthy side. Notice nearly the same diagram pattern between healthy anterior tibial muscle and transferred head of gastrocnemius muscle after reinnervation.

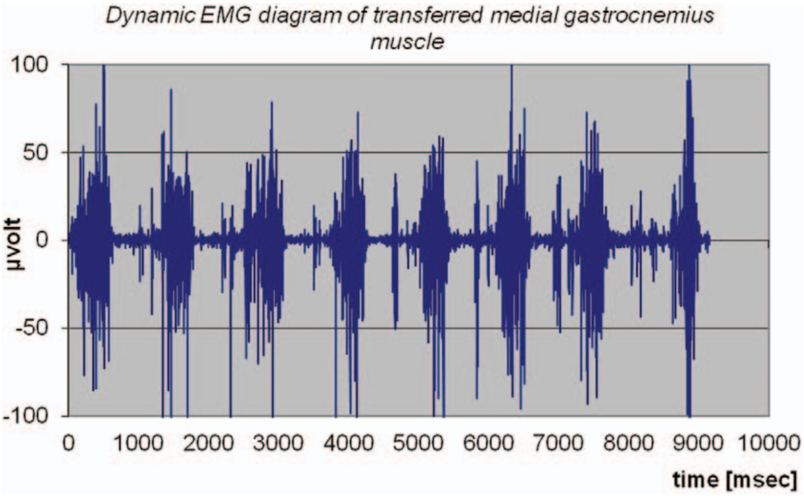

Fig. 3. Dynamic electromyography (*EMG*) during seven steps for the transferred head of the gastrocnemius muscle. Notice nearly the same diagram pattern between healthy anterior tibial muscle and transferred head of gastrocnemius muscle after reinnervation.

results in tenodesis, which limits plantar flexion and active range of motion.[12] Two different transfer routes, either through the interosseous membrane or around the tibia, are described, but both show significant reduction of range of motion.[12,17] The interosseous route suffers from adhesions in the interosseus membrane.[12] The use of a subcutaneous tunnel for the circumtibial transfer creates a fulcrum for the joint, reducing the already small range of tibial posterior muscle excursion.[12] Successful tibial posterior muscle transfer, however, depends on a certain level of tenodesis because, at rest, the muscle has to antagonize the by far stronger plantar-flexing muscles.[12] Finally, tibial posterior muscle transfer suffers from long-term complications, including hindfoot valgus deformity, arthritis, and flat foot deformity resulting from changes to the tension of the plantar aponeurosis.[18,19]

Our surgical approach uses the gastrocnemius muscle instead of the tibial posterior muscle for several reasons. The gastrocnemius muscle has a well-suited size, topography, and neurovascular anatomy, in addition to adequate strength and range of excursion to substitute for the nonfunctioning muscles of the anterior and/or lateral compartment.[14,20] A single motor branch of the tibial nerve innervates the gastrocnemius muscle. The close anatomical relation between this motor branch and the proximal part of the

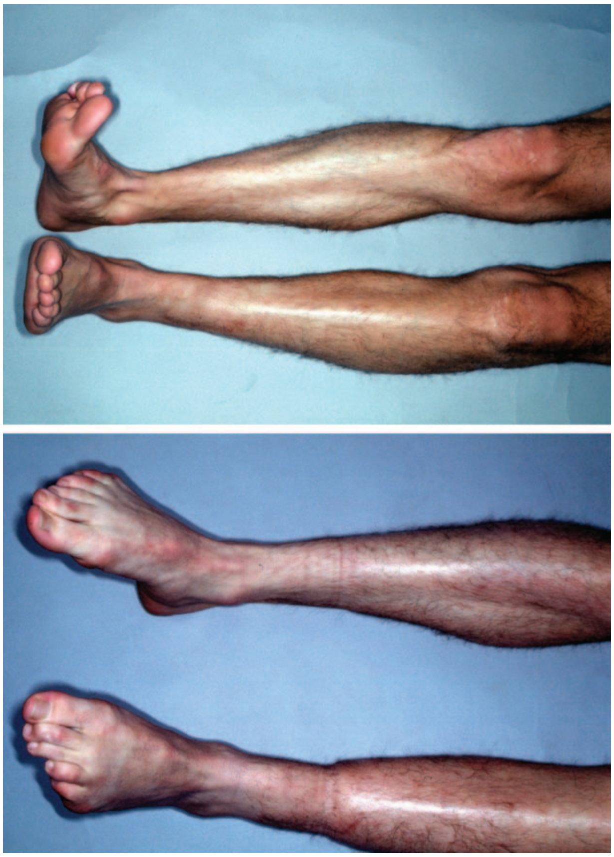

Fig. 4. (*Above*) Postoperative view with full range of voluntary dorsiflexion in the ankle joint with an excellent result. (*Below*) Postoperative view with full range of voluntary plantar flexion with an excellent functional outcome.

Table 2. Functional Outcome of Patients with Drop Foot Deformity Treated with Neuromusculotendinous Transfer of Gastrocnemius Muscle

	Value
Excellent	10
Normal pattern of dynamic EMG	
Normal ankle joint motion, balance	
Stable, fully automatic walking	
Active dorsiflexion ≥0 degrees	
Active plantar flexion ≥40 degrees	
Active ROM of ≥40 degrees and more	
Good	4
Sufficient pattern of dynamic EMG	
Sufficient ankle joint motion, with minimal foot inversion	
Stable automatic walking	
Active dorsiflexion between 5 and 0 degrees	
Active plantar flexion of ≥40 degrees	
Active ROM of ≥30 degrees	
Satisfactory	3
Sufficient pattern of dynamic EMG	
Stable ankle joint motion	
Automatic walking but with occasional dropping of the foot	
Active ROM of ≥20 degrees*	
Fair	1
Improved walking with evident dropping of the foot	
Insufficient active dorsal flexion (−15 degrees)	
Active ROM <20 degrees	
Total	18

EMG, electromyography; ROM, range of motion; AROM, active range of motion.
*Two of three cases had dual transfer of the gastrocnemius muscle and had a very stable ankle joint without any inversion, but had reduced ROM because of a tenodesis effect.

deep peroneal nerve (Fig. 2)[14,21] makes tension-free neurorrhaphy close to the muscle possible and minimizes muscle denervation time. As a consequence of this approach, the patient can use the transferred muscle voluntarily right after successful reinnervation. Only postoperative physiotherapy is needed, to build up the muscle strength. We have to point out, however, that nerve regeneration takes time, and the rehabilitation period required to gain full muscle strength may therefore last up to 18 months. Another major advantage is that our surgical approach does not require a tenodesis effect. Because of the orthotopic reinnervation, the transferred muscle acts independently during movement. By transferring the gastrocnemius muscle, the anterior and lateral compartments are strengthened, as opposed to muscle balance, and power is restored. The straight and superficial route chosen for the transfer of the muscle-tendon unit allows a normal gliding pattern and prevents adhesions. Finally, this transfer does not cause any considerable functional or aesthetic defects.[21]

When examined at follow-up, most of our patients showed functional gait patterns confirmed by dynamic electromyographic examination and gait analysis (Fig. 3). All of our patients experienced significant improvement of gait and had achieved almost normal plantar flexion. Remarkably, active range of motion was found to be above 40 degrees in 13 of 18 cases (72 percent). The remaining five patients already had reduced passive movement in the treated ankle before surgery, a condition that could not be influenced by the applied treatment. Our results appear to be superior to other published data using conventional tibial posterior tendon transfer. Although Hove and Nilsen[11] reported a range of motion of more than 40 degrees in patients treated with tibial posterior transfer, they could obtain this result in only six of 20 cases (30 percent).[11,12,15–17,22,23]

We have learned that the restoration of the anterior compartment by transfer of the lateral head leads to less satisfactory results than transfer of the medial head. Not only was the cosmetic outcome slightly disappointing, but the muscular strength was also found to be less than expected. This was related to the fact that the transferred lateral gastrocnemius muscle was routed over the fibula head, which subsequently acted as a fulcrum.[14]

In patients with peroneal nerve lesions, the muscles of the lateral compartment often partly recover and regain sufficient function to balance the foot. Stable dorsal flexion may then be sufficiently restored by transferring only the medial gastrocnemius muscle head and by using a described common attachment point together with motor nerve coaptation. In cases where the muscles of the lateral compartment and anterior compartment are completely paralyzed or damaged but only one gastrocnemius muscle head is chosen to be transferred, the main tension has to be applied to the extensor digitorum longus tendon to avoid foot inversion. We are currently using the medial head of the gastrocnemius muscle to restore the anterior compartment and both heads to restore both compartments. A medial head replaces the missing function of the muscle of the anterior compartment and is reinnervated by the deep peroneal nerve. The lateral head is used for foot stabilization and substitution of lateral compartment muscles but left under tibial nerve innervation. This lateral head of the gastrocnemius muscle creates tenodesis with plantar flexors, reducing plantar flexion and generally active range of motion. However, this does not produce any functional difference in walking except in running.

To achieve these results in patients to be treated with this original method, the patients have to be selected carefully.[14] The proximal part of the peroneal nerve has to be viable to provide good reinnervation. Thus, all patients with peroneal nerve damage located farther proximally, such as ischiadic nerve injury, avulsed peroneal nerve damage, or paralyses caused by nontraumatic reasons, have to be excluded. Determination of the zone of peroneal nerve injury proximally can be difficult (e.g., in avulsion mechanism insults such as knee dislocations). Clinical history, Tinel sign, and ultrasound and magnetic resonance imaging evaluations are routinely performed preoperatively. However, the suitability of the peroneal nerve stump for coaptation is ultimately determined intraoperatively by histologic examination and appearance under the operating microscope. Gastrocnemius muscle transfer is carried out only if more than 70 percent of the nerve fibers appear healthy. Otherwise, the classical tibial posterior muscle transfer is performed. Likewise, patients with fixed deformities that reduce the ankle's passive range of movement or injuries involving muscles innervated by the tibial nerve are not suitable candidates for this treatment. The best result can be achieved by patients with muscle necrosis after compartment syndrome (the deep peroneal nerve is uninjured) or a peroneal nerve lesion at the level of the fibula head.

The concept of a direct nerve transfer of a tibial motor nerve branch to the deep peroneal nerve as an alternative option to restore ankle dorsiflexion in cases of peroneal nerve injury has been proposed by Nath et al.,[24] Giuffre et al.,[25] and Strazar et al.,[26] performing in one case report, nerve transfer to the peroneal nerve, using the branch from the lateral gastrocnemius muscle to the tibialis anterior muscle branch. This latter "nerve transfer–only" approach may be a simpler technique for high peroneal nerve injury, avoiding nerve grafting technique, but the peroneal muscle group will be innervated by the tibial nerve, generating an antagonistic nerve supply and poorer results.

Our surgical approach restores voluntary dorsiflexion, without influencing regular plantar flexion and normal walking patterns, without depending on difficult reeducation training processes. The transfer of gastrocnemius muscle and subsequent reinnervation of the transferred muscle by the peroneal nerve is a novel approach for overcoming the limitations of previous methods and should be considered to be the method of choice in a carefully selected group of patients. Our long-term experience with this technique since 1989 has until now proved the superiority of this technique compared with all other present procedures.

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