CME

Current Concepts in Lower Extremity Amputation: A Primer for Plastic Surgeons

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Learning Objectives: After studying this article, the participant should be able to: 1. Understand the goals of lower extremity reconstruction and identify clinical scenarios favoring amputation. 2. Understand lower extremity amputation physiology and biomechanics. 3. Review soft-tissue considerations to achieve durable coverage. 4. Appreciate the evolving management of transected nerves. 5. Highlight emerging applications of osseointegration and strategies to improve myoelectric prosthetic control.

Summary: Plastic surgeons are well versed in lower extremity reconstruction for traumatic, oncologic, and ischemic causes. Limb amputation is an increasingly sophisticated component of the reconstructive algorithm and is indicated when the residual limb is predicted to be more functional than a salvaged limb. Although plastic surgeons have traditionally focused on limb salvage, they play an increasingly vital role in optimizing outcomes from amputation. This warrants a review of core concepts and an update on emerging reconstructive techniques in amputee care. *(Plast. Reconstr. Surg.* 152: 724e, 2023.)

Lower extremity (LE) amputations are among the oldest described surgical procedures. Hippocrates, circa 400 BC, documented one of the earliest written accounts in which he described life-saving amputations of gangrenous limbs.[1] Hemorrhage control with tourniquets and arterial ligation enabled surgeons to completely amputate the necrotic tissue, but before the discovery of anesthesia in 1846, amputations continued to be performed as hastily as possible, with high mortality.

After the widespread implementation of antisepsis and reliable anesthesia, safe, elective amputation became possible. Even still, reconstructive options for compromised limbs remained limited. Historically, before innovations in surgical technique, the most effective treatment for open fractures was amputation.[2] Over the past 60 years, however, significant advances in vascular repair, fracture fixation, and microvascular tissue transfer have substantially increased the ability to salvage impaired limbs, relegating amputation to a secondary role in the management of lower extremity trauma, infection, cancer, and vascular compromise.[3,4]

Given the profound physical and psychological effects of amputation, both patients and surgeons naturally aspire to salvage limbs when possible, with amputation often considered an ostensible failure. However, it is increasingly clear that the "successful" salvage of a painful, stiff, or nonfunctional limb delays rehabilitation and impairs quality of life.[5] This consideration has become increasingly important with ongoing advances in the reconstruction options and advanced prosthetics available to amputees.

The primary goal of limb reconstruction is to maximize residual limb function, minimize pain, and confer the highest quality of life possible.[6] To best determine which treatment approach will achieve this, reconstructive surgeons must understand the capabilities and limitations of both limb salvage and amputation. Innovative amputation techniques, peripheral nerve management, and prosthetic capabilities have improved outcomes

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and elevated the role of amputation in reconstructive algorithms. The diverse skillset, knowledge of all tissue types, and holistic consideration of both form and function has positioned the reconstructive surgeon to assume an integral role in the multidisciplinary effort at limb restoration, whether through salvage or amputation. Nevertheless, a comprehensive limb salvage center must incorporate the expertise of all pertinent specialties, surgical and medical, to provide a patient-centered approach.[7] The Global Limb Anatomic Staging System guidelines, which describe the necessary components for developing a limb salvage program, include concepts such as protocol-driven care, methods of objective outcome measurement, and collaboration between relevant surgical and medical subspecialities (eg, orthopedics, plastic surgery, physical medicine and rehabilitation, palliative care).[8] However, these considerations are also necessary for successful care of patients who undergo lower extremity amputation.

EPIDEMIOLOGY

There are an estimated 2 million limb-loss patients in the United States, with over 185,000 major extremity amputations performed annually.[9] Amputations proximal to the ankle are classified as major and are the focus of this review.

Peripheral vascular disease, most commonly the sequelae of diabetes mellitus, accounts for nearly 80% of major LE amputations.[10] Traumatic and oncologic indications constitute 17% and 2%, respectively.

The cause of limb impairment tends to correlate with baseline functional status, which is a cardinal consideration in determining the optimal treatment of lower extremity compromise. Ischemic amputations more commonly occur in older, more morbid, and less functional individuals as compared with the typically younger, more active trauma population.[10,11] Thus, a comprehensive approach to limb reconstruction must prioritize individualized patient goals in the context of their acute medical condition, longstanding comorbidities, and baseline functional status.

AMPUTATION VERSUS SALVAGE: MAXIMIZING FUNCTION

The decision to salvage or amputate an impaired limb should be predicated on which intervention is predicted to result in the most functional outcome. A multidisciplinary approach is recommended with close collaboration with the pertinent orthopedic, vascular, trauma, endocrine, oncologic, psychology, and rehabilitative services.[12] Before committing to a treatment strategy, the extent and prognosis of impairment and the patient's baseline functional status should be understood.

In the treatment of peripheral vascular disease patients, consultation with a vascular surgeon and angiographic assessment of limb blood flow should be obtained. Healing potential can be assessed using the ankle-brachial index and toe pressures. Revascularization efforts should be exhausted before amputation except when there is necrosis of a major portion of the limb or in cases of life-threatening infection.

In oncologic cases, the treatment strategy must prioritize disease eradication while optimizing residual limb function. The extent to which limb length and function can be salvaged is largely dependent on tumor characteristics, and it has greatly expanded with advances in chemotherapy and radiotherapy protocols. Involvement of major neurovascular structures is not a contraindication to limb salvage if reconstructive options exist, but the diminution in function resulting from major nerve sacrifice must be carefully considered. In most cases, a paucity of data exists to conclusively determine when nerve grafting, nerve transfers, tendon transfer, or amputation may yield superior function. The recent advent of nerve transfers in the lower extremity offer great promise, but clinical outcomes remain poorly defined.

LE trauma is the most well studied indication for amputation. The Lower Extremity Assessment Project study notably found no functional difference between early amputation or limb salvage in patients with high-energy LE trauma.[13,14] Notably, psychosocial and medical predictors of poor long-term outcomes after limb salvage or amputation, such as lack of a stable social support network, low level of self-efficacy, active smoking status, and lower socioeconomic status, were the same across both groups. However, subsequent studies have since identified marked improvements in function, pain, and overall well-being when LE combat injuries are managed with early amputation.[15–18] A number of scoring systems aimed to identify traumatized limbs that would benefit from early amputation, but validation attempts revealed significant shortcomings in their utility.[19,20] With the current shift toward incorporating patient-reported outcomes (PRO) as a standard part of care, it is essential to understand the available assessment tools for use in the lower extremity amputee patient population. Because of the heterogeneous causes of lower extremity amputation within this population, ranging from oncologic resection to limb salvage after trauma, there are a range of possible PRO assessments. Several specific tools such as the Prosthesis Evaluation Questionnaire have been used to assess the patient's self-reported perceptions of their psychological and functional well-being after amputation and prosthesis placement.[21] Others, such as Musculoskeletal Tumor Society scoring system and Toronto Extremity Salvage Score, have been developed, validated, and translated into multiple languages for patients with lower extremity sarcoma. However, a comprehensive, validated PRO instrument for both amputation and salvage does not yet exist, highlighting a distinct need in the field.[22]

Ultimately, the decision to salvage or amputate requires a patient-centered approach that marries the surgeons' clinical gestalt with the patient's goals and preferences. Given the permanence of amputation, early efforts favor limb salvage in the absence of contraindications (Table 1). Emergent revascularization and débridement of devitalized tissues should be performed expeditiously, which also enables a thorough evaluation of the extent of injury. The psychological impact of major limb loss is immense, and patients are often reticent to accept an amputation early in their treatment course. Every effort should be made to have a prosthetist meet with patients before amputation to improve understanding of the level of function offered by commercially available prosthetics.

Even when limb salvage is pursued, it is important to regularly reevaluate the patient's progress with rehabilitation, as conversion to amputation may become appropriate.[23] A conversion to late amputation after a protracted salvage attempt can achieve results similar to early amputation in a majority of patients, but may be associated with increased rates of mood disorders.[24–26] Irrespective of treatment modality, social support and self-efficacy significantly impact outcomes and should factor into decision-making.[14]

AMPUTATION LEVEL

Energy expenditure during ambulation is inversely proportional to the residual limb length.[27] Thus, the most distal level of amputation compatible with wound healing should be selected. This will provide the most advantageous lever arm and is associated with an increased likelihood of ambulation, return to work, and quality of life.[28] Transtibial (TT) and transfemoral (TF) are the most common major amputation levels and are associated with a 40% and 90% increase in energy expenditure, respectively.[29]

Because of the exponential increase in energy demands with TF amputation, every effort should be made to preserve the knee joint. In cases where damage to soft tissues would otherwise necessitate proximal amputation, local or free tissue transfer can be used to facilitate a more favorable level of amputation. Similarly, vascularized bone flaps have been described to stabilize proximal fractures, increase residual length, and preserve amputation levels.[30]

A short residual limb can complicate prosthesis suspension. Generally, 5 cm of residual bone is the minimum required length to securely fit a conventional socket-based prosthesis.[31] Conversely, an excessively long residual limb may leave insufficient space to fit necessary joint components at the same level as the contralateral intact limb, potentially complicating gait patterns. It is generally recommended that the osteotomy for TF and TT amputations be performed at least 10 cm above the knee and 17 cm above the ground, respectively (Fig. 1).[29,32]

A knee disarticulation, or through-knee (TK) amputation preserves more length than the TF level and may improve prosthesis suspension by using the femoral condyles to anchor the socket. Current guidelines recommend against TK amputations given the asymmetric knee joint axis and poor functional outcomes reported in the Lower Extremity Assessment Project trial.[28,33] However, a recent meta-analysis found 104 TK amputees were more likely to ambulate 500 m and reported higher quality-of-life scores compared with 888 TF amputees.[34] Diaphyseal shortening in conjunction with TK amputation has been described as a strategy for maintaining the femoral condyles for suspension, while avoiding discrepancy of the knee joint axis.[35,36] Before embarking on a nonstandard amputation level, consultation with a prosthetist is recommended to ensure specialty components are available.

Table 1. Absolute Contraindications for Limb Salvage

Warm ischemia >6 hr
Critically ill, threat to life
Unrepairable vascular injury

SOFT-TISSUE CONSIDERATIONS

Skin

A durable, well-padded soft-tissue envelope is needed to tolerate weight bearing and prosthesis suspension. Incisions should not reside over bony prominences. Of note, modern prostheses

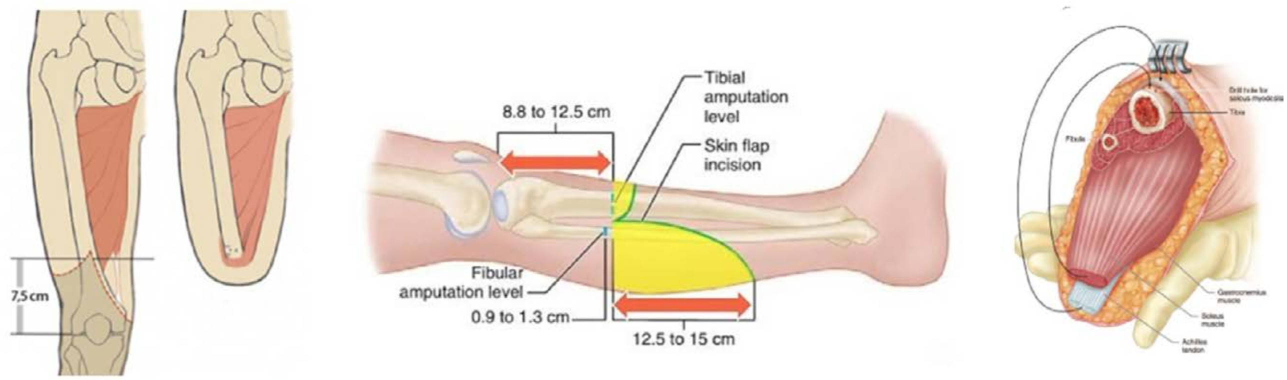

Fig. 1. LE amputation techniques. (*Left*) In the TF amputation, a fishmouth incision is made distal to the level of the bone transection, with eventual posterior positioning of the final scar. Ideally, the femoral osteotomy is performed 10 to 15 cm above the knee joint. Myodesis of the adductor magnus to the residual femur is necessary to prevent abduction contracture of the residual femur. (*Center*) In the TT amputation, a tibial osteotomy is performed approximately 14 to 18 cm below the tibial tuberosity and ensuring there is at least 17 cm clearance from the ground. The tibia osteotomy is beveled anteriorly to avoid a bony prominence, and the fibula is osteotomized 1 cm proximal to the tibia. (*Right*) The anterior, lateral, and deep posterior musculature are transected at the level of the anterior skin incision. The soleus-gastrocnemius complex is myodesed to the anterior tibia through drill holes, and the anterior and lateral compartment muscle fascia is closed to the lateral portion of the soleus-gastrocnemius complex.

distribute weight-bearing forces throughout the surface of the socket, and thus, incisions may safely cross the terminal end of the stump if there is sufficient soft-tissue coverage, although this is usually avoided when possible. Broad-based fasciocutaneous flaps are used and should remain attached to the underlying musculature to maximize perfusion. The skin is closed without undue tension while also avoiding redundancy that can complicate prosthesis suspension. Some degree of soft-tissue laxity is unavoidable, as intraoperative soft-tissue swelling will resolve postoperatively to create a relative imbalance between residual limb volume and surface area that is worsened by postamputation muscle atrophy. Obesity further contributes to soft-tissue redundancy that can interfere with socket suspension, particularly in TF amputees who often experience difficulties with an adductor roll. In these cases, a vertically oriented thighplasty can excise the redundant skin and fat to facilitate fitting.[37,38]

Several fasciocutaneous flap designs have been described for use in the setting of amputation, including the long-posterior, skew, and sagittal flaps. A Cochrane review found no difference in primary healing between these flap designs for elective TT amputations.[39] In the presence of wet gangrene, however, a staged guillotine amputation improved primary stump healing as compared with single-staged long-posterior flap TT amputation.[39]

In severely traumatized extremities, traditional skin flap designs are often not possible. In such cases, limb length preservation is prioritized, and coverage is achieved through other means. The viable spare parts of the amputated limb can be used as a fillet flap to close the defect. Microvascular free tissue transfer is warranted to ensure adequate residual limb length.[6] Flap selection must balance the needs of the defect with the goal of limiting functional morbidity in the upper extremity and trunk. Although muscle flaps such as the latissimus dorsi flap can provide ample soft-tissue coverage, diminished shoulder adduction after harvest can interfere with the patient's ability to perform transfers and use crutches. Fasciocutaneous flaps provide durable soft-tissue coverage that are easily recontoured in the setting of residual limb atrophy. Fasciocutaneous flaps based on the circumflex scapular axis can provide sufficient coverage and variable geometries that enable coverage of a large, irregular residual limb soft-tissue defect (Fig. 2). In addition, there is minimal functional morbidity and the soft tissues of the back tend to be spared even in cases of multiple extremity trauma.[40]

Less sophisticated reconstructive methods such as subatmospheric wound therapy, external wound closure devices, and skin grafting have been successfully used when free flaps are not indicated.[41,42] However, these should generally be avoided over the terminal end when possible to avoid thin, adherent scars over a bony prominence.[41] Troublesome terminal scars and grafts may be excised secondarily once edema and limb atrophy stabilize and acute medical problems are optimized.

Fig. 2. (*Left*) A traumatic transtibial amputation with insufficient soft-tissue coverage. (*Center*) To preserve length, a parascapular fasciocutaneous free flap was harvested to fit the dimension of the defect. (*Right*) The flap contours well and provides durable soft-tissue coverage.

Muscle

Transected muscles will retract and undergo disuse atrophy unless their distal fixation point is reestablished.[43] Failure to do so may result in inadequate distal padding and contractures from unbalanced muscle groups. When possible, sectioned muscles should be reinserted under physiologic tension. This is commonly achieved with a myodesis in which the distal muscle fascia is directly affixed to bone. This is imperative in TF amputations where the powerful adductor magnus is disinserted and the abductors remain attached to the femur. Without an adductor myodesis, these patients experience high rates of abduction contractures, greatly limiting the likelihood of ambulation.[44] In the TT amputation, the superficial posterior musculature is generally myodesed to the anterior tibia to pad the terminal amputation stump. In addition to balancing forces acting on the residual joints with a myodesis, a myofascial closure of overlying muscle compartments further reinforces the closure and serves to limit relative motion between the skeletal and soft-tissue components (Fig. 1).

A traditional myodesis inherently sacrifices the dynamic agonist-antagonist muscle relationship. In the native limb, muscle spindle and Golgi tendon organs in agonist-antagonist muscles serve as stretch receptors. They transmit muscle tension information to the cortex, which generates proprioceptive joint position awareness. In an attempt to restore this feedback, a novel agonist-antagonist myoneural interface technique has been described for TT amputations in which distal tendon transfers are performed to recreate flexion-extension and eversion-inversion agonist-antagonist pairs in the residual limb to provide proprioception from the phantom ankle.[45] [**See Video 1 (online)**, which displays agonist-antagonist myoneural interface technique.]

Long-term outcome data do not yet exist for this technique, but early reports highlight the value of proprioceptive feedback and bidirectional control for advanced myoelectric limbs.[45]

Nerve

Traditional traction neurectomy entails sectioning of nerves under tension, allowing the proximal end to retract deep within the soft-tissue envelope, where the terminal neuroma that develops will be remote from the distal weight-bearing surfaces. However, LE amputees treated with traction neurectomy continue to experience high rates of residual limb pain (RLP) and phantom limb pain (PLP).[46] This greatly impairs prosthesis use, quality of life, and overall functionality.[47] Symptomatic terminal neuromas are one of multiple causes of RLP. The exact cause of PLP remains unclear but is thought to arise from complex peripheral sensitization and cortical remodeling induced by a combination of pathologic afferent signals from terminal neuromas and the absence of physiologic feedback from the amputated limb segment.[48,49]

Contemporary approaches to nerve management favor a reconstructive approach in which transected nerves are provided distal reinnervation targets (Fig. 3).[50] It is hypothesized that

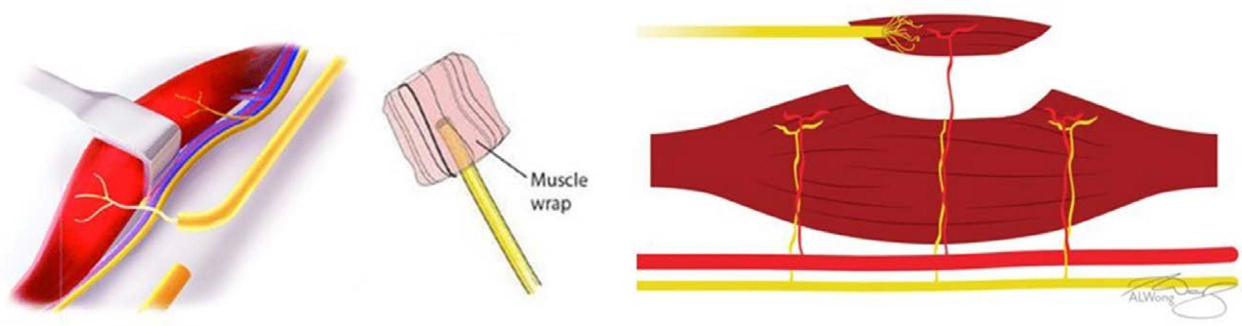

Fig. 3. A depiction of three regenerative approaches to manage transected nerves in an attempt to reduce postoperative pain. (*Left*) With targeted muscle reinnervation, a transected peripheral nerve is transferred and coapted to the motor branch nerve of a healthy residual limb muscle, enabling regeneration through the native pathway. (*Center*) A transected nerve is enveloped and fixed to a muscle graft to form a regenerative peripheral nerve interface construct. Regeneration with regenerative peripheral nerve interfaces occurs by means of direct neurotization of the muscle graft. (*Right*) Using the vascularized denervated muscle target regenerative approach, a denervated muscle flap is raised on a vascular pedicle and a transected nerve is fixed to this flap. Regeneration occurs by means of direct muscle neurotization. Reprinted with permission from Tuffaha SH, Glass C, Rosson G, Shores J, Belzberg A, Wong A. Vascularized, denervated muscle targets: a novel approach to treat and prevent symptomatic neuromas. *Plast Reconstr Surg Glob Open* 2020;8:e2779.

reinnervating a muscle target will restore afferent inhibitory pathways, limit neuroma formation, and prevent pain sensitization.[46] Although sound in theory, the lack of a comprehensive understanding of postamputation pain pathways remains a significant barrier to the rational refinement of surgical techniques intended to treat or prevent pain. The following are surgical techniques that have been used for nerve management in lower limb amputations (Table 2).

Targeted Muscle Reinnervation

Initially described by Dumanian and Kuiken to improve myoelectric prostheses control, targeted muscle reinnervation (TMR) entails the transfer of transected peripheral nerves to nearby motor branches of residual muscles. The coaptation is performed close to the target muscle, allowing quick reinnervation of the freshly denervated muscle. A randomized controlled trial compared TMR to neuroma excision and implantation into innervated muscle for the treatment of RLP and PLP and found a significant improvement in PLP with TMR. RLP also improved in the TMR group but did not reach strict statistical significance.[46]

TMR targets and techniques have been described for TT and TF amputations[46,51,57–59] and are increasingly being used preventatively at the time of primary amputation and secondarily to treat postamputation RLP and PLP (Figs. 4 and 5).[52,60–62] [**See Video 2 (online)**, which displays neuroma management and targeted muscle reinnervation: part 1. The video details transtibial amputation with TMR using tibial nerve–to–nerve to the soleus coaptation. **See Video 3 (online)**, which displays neuroma management and targeted muscle reinnervation: part 2. The video details transtibial amputation with TMR using common peroneal nerve–to–nerve to the lateral gastrocnemius coaptation.]

Downsides of this technique include the need for additional incisions and dissection to access target motor nerves, the need to denervate residual muscle groups that might otherwise be used as padding or for other adjunctive techniques, and the potential paucity of motor nerve targets at proximal amputation levels. In addition, there is concern that the large size mismatch between donor and recipient nerves can result in neuroma-in-continuity as a result of axonal escape. Theoretically, this can be ameliorated by performing the coaptation at or within the denervated muscle target.[63–65]

Regenerative Peripheral Nerve Interface

Regenerative peripheral nerve interfaces (RPNI) are muscle grafts secured to the transected nerve ends to serve as reinnervation targets for the regenerating axons. As with TMR, RPNI was originally developed to amplify signals from the transected nerve stumps to improve prosthesis control.[66] Unlike TMR, RPNI does not involve a nerve coaptation, and thus reinnervation must occur by means of direct neurotization of the muscle graft. [**See Video 4 (online)**, which displays neuroma management and RPNIs.] This is possible because the muscle grafts are denervated at the time of harvest and

Table 2. Summary of Surgical Techniques for Management of Transected Nerves

	Description	Mode of Neurotization	Outcomes	Notes
TMR	Transected peripheral nerve is coapted to a nearby motor branch supplying residual muscles within the remnant limb.	Nerve-to-nerve coaptation	72% of primary TMR patients experienced phantom limb pain in the first month postoperatively, with an eventual decline to 13% at 6 mo; no patients in this cohort developed postoperative neuroma/residual limb pain after TMR (level I evidence)[51,52]	• Requires expendable recipient motor nerves • May necessitate additional incisions on the residual limb to access motor branches • Size-mismatched coaptation and axonal escape is a concern for painful neuroma prevention • Robust EMG signal generation, enabling operation of myoelectric prostheses
RPNI	A nonvascularized, denervated muscle graft is wrapped around the end of transected peripheral nerves. Regeneration occurs by means of direct neurotization of the muscle graft.	Direct neurotization	Patients report a 71% reduction in neuroma pain postoperatively, and 53% reduction in phantom pain (level IV evidence)[53]	• Major benefits with regard to technical ease and versatility; no additional surgical exposure required. • Size-limited by virtue of being nonvascularized; the amount of muscle tissue required to prevent neuroma formation for a given sized nerve has yet to be defined • Necrosis is a concern if RPNI is too large or wound bed is not hospitable; some degree of fibrosis and/or resorption is expected in all cases. • Generates and amplifies EMG signals from motor nerves that can be used for control of myoelectric limb prostheses[54,55]; in comparison to TMR, more signals can be generated that are smaller in amplitude
VDMT	A denervated muscle flap is elevated and isolated on its vascular pedicle before being secured to the end of a transected peripheral nerve.	Direct neurotization	Short-term outcomes for patients who underwent secondary VDMT for symptomatic neuromas following upper extremity amputations showed complete improvement in neuromatous pain (level VI evidence)[56]	• Similar to RPNI with the added benefit of maintaining vascular perfusion to target muscle; not size limited; less versatile with limited application in some anatomical locations (ie, hands, face) • More flexibility than TMR; vascular leashes supplying muscle are more abundant and accessible than are motor branches • VDMTs can be harvested while preserving the majority of the donor muscle and its associated function • Limited outcomes data

TMR, targeted muscle reinnervation; EMG, electromyographic; RPNI, regenerative peripheral nerve interface; VDMT, vascularized denervated muscle target.

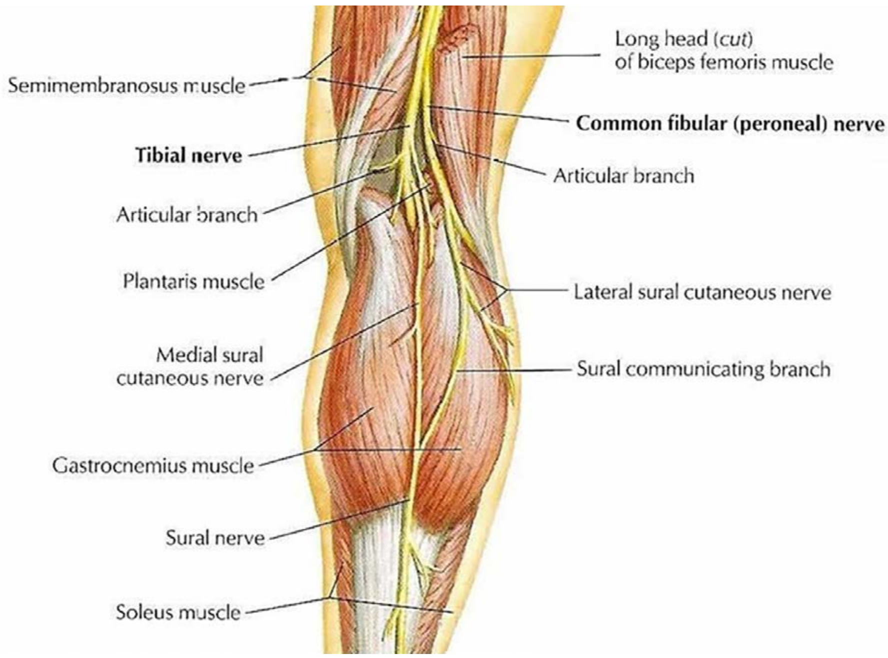

Fig. 4. Illustration of a reconstructive approach to manage transected nerves in a transtibial amputation to provide nerves with distal reinnervation targets. The tibial and common peroneal nerves are coapted to the motor branches to the soleus and lateral gastrocnemius, respectively, using the TMR technique. The tibial and peroneal contributions to the sural nerves are managed using regenerative peripheral nerve interface muscle grafts harvested from the gastrocnemius.

therefore receptive to reinnervation by means of direct neurotization [**see Video 3 (online)**]. The muscle grafts can be harvested without transecting motor nerves and denervating a donor muscle in the residual limb, as occurs with TMR; however, the avascular nature limits the size of muscle grafts and has raised questions as to whether RPNIs provide sufficient receptive capacity for large-caliber donor nerves.[67] Importantly, the amount of viable muscle tissue needed to accept a given number of regenerating axons has yet to be defined.

Among patients who underwent secondary RPNI for the treatment of RLP, 71% of patients reported decreased neuroma pain and 53% saw a decrease in PLP.[53] RPNI has also been successfully used primarily at the time of amputation to prevent PLP.[68]

Vascularized Denervated Muscle Target

Vascularized denervated muscle target (VDMT) is a recently described approach to manage neuromas that draws on the advantages of both TMR and RPNI.[67] It entails the elevation of a muscle flap that is fully elevated on a vascular pedicle. [**See Video 5 (online)**, which displays VDMT for sciatic nerve neuroma after above-knee amputation.]

In doing so, the muscle flap is denervated and, as with RPNIs, receptive to reinnervation by means of direct neurotization from the proximal nerve stump to which it is secured. However, because VDMTs are vascularized, they are less susceptible to fibrosis and resorption that occurs with muscle graft healing and are less size-limited than RPNIs. Unlike TMR, VDMT does not require a recipient motor nerve or that an entire muscle to be sacrificed, expanding the number of potential targets. Limited outcomes data exist for this technique and further follow-up is needed.

In addition to surgical techniques, comprehensive medical management of pain can limit chronic postsurgical pain. Uncontrolled acute surgical pain is known to increase the conversion to chronic pain.[69] Preemptive analgesia with regional blocks has demonstrated utility and is thought to help limit central pain sensitization.[70] Multimodal, opioid-sparing pain management reduces rates of chronic pain and gabapentinoids have demonstrated limited efficacy in preventing and treating PLP.[71,72]

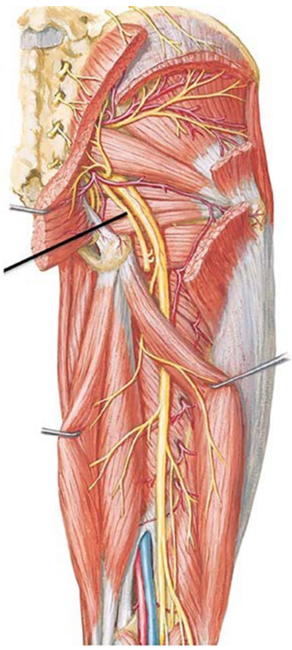

Fig. 5. A reconstructive approach to manage transected nerves in a transfemoral amputation. Internal neurolysis of the sciatic nerve separates the tibial and peroneal fascicles. The tibial component of the sciatic nerve is coapted to freshly transected motor branches entering the semimembranosus or semitendinosus. The peroneal portion of the sciatic nerve is coapted to a motor branch innervating the long head of the biceps femoris. Regenerative peripheral nerve interface muscle grafts can be used to manage the posterior femoral cutaneous nerve and anteriorly for the saphenous nerve (not shown).

BONE

A stable skeletal construct is required to tolerate functional weight bearing. The presence of proximal fractures is not necessarily an indication for more proximal level amputations. Rather, these fractures can be stabilized, allowing for a more functional distal amputation.[73] In cases of segmental loss or insufficient residual bone length, vascularized bone flaps, such as a fillet fibula, can help achieve osteosynthesis and preserve length.[74,75] Similarly, femoral lengthening has been used to achieve sufficient length to accommodate a conventional socket.[76–78]

Control of the residual bone is achieved by means of the remaining muscle attachments and myodesis. At the TT level, discordant tibiofibular movement, often referred to as “chopsticking,” can develop, which can be painful and impair ambulation. Ertl described a tibiofibular synostosis technique in which a fibular strut, attached by a periosteal sleeve, is interposed between the two bones to provide a stable platform for weight bearing.[79] There is conflicting evidence as to the utility of this technique. As such, it is usually reserved for highly active patients or to treat symptomatic chopsticking, when residual limb length allows.[79]

POSTOPERATIVE CARE AND REHABILITATION

Postoperative dressings aim to facilitate healing and reduce edema. Rigid dressings have been advocated for their superior protection and compression.[32] Still, it remains unproven whether rigid dressings are superior to soft elastic dressings, and application requires additional logistic coordination.[80]

Physical therapists should be involved early in the postoperative period to protect against contractures and begin balance, strength, and mobility training.[11] Stump shrinkers are started when sutures are removed to help clear edema and shape the residual limb. Prosthesis fitting does not generally occur until wounds are healed, edema has resolved, and there is sufficient capacity to tolerate local loading. It is clear, however, that a shorter time to first fitting is associated with improved prosthesis use and satisfaction; the first fitting should ideally occur within 6 to 8 weeks postoperatively.[81]

The basic function of LE prostheses is to support the body and facilitate ambulation. The socket is the interface between a prosthesis and the residual limb and is most commonly suspended to the limb with subatmospheric pressure generated between a liner and socket. Joint components can be passive, semipassive, or motorized/active, and are configured to the patient’s specific functional needs. The majority of amputees are not fitted with advanced microprocessor-equipped prosthetics, which can be expensive, heavy, and more prone to breakdown. We anticipate that the utility and uptake of advanced prosthetics will increase in the near future, with ongoing refinements and reduction in cost.

Myoelectric Controlled Prostheses

In contrast to conventional body-powered prostheses, myoelectric control uses electromyographic signals generated from muscles in the residual limb to manipulate the artificial limb. These signals can be used to initiate active knee extension and ankle plantar flexion to restore the user’s ability to perform activities that are currently limited with conventional prostheses, such as stair climbing, walking backward, and jumping.[82,83]

Selective nerve transfers can improve the intuitiveness of prosthesis control. For instance, spontaneous ankle dorsiflexion and plantarflexion can be restored in TF amputees with transfers of the common peroneal and tibial nerves, respectively.[84] More distal TT amputees retain more native electromyographic signals, which have been harnessed to improve multiaxis ankle control without nerve transfers.[83,85] Although exciting, these devices remain experimental, and there are currently no commercially available myoelectric prostheses for the lower limb.[82,84] Furthermore, the cost of these devices is a significant barrier to widespread use. A 2009 study by Seelen et al. in The Netherlands showed that overall costs for myoelectric lower limb prostheses (including cost of the initial surgical intervention and device), the health care costs of regular maintenance, and human capital and productivity costs was over $90,000.[86]

Osseointegration

Despite dramatic improvements in socket designs, nearly one-third of LE amputees report significant discomfort fitting their prosthesis.[81] Osseointegration (OI) promises to overcome socket-based prosthetic complications, including skin breakdown, rashes, pain, and heaviness, by directly fixing the prosthesis to bone. OI enables direct load transfer from the prosthesis to bone, bypassing the soft-tissue envelope. This mechanical advantage decreases energy expenditure, eases donning and doffing, increases prosthesis embodiment, and can even provide enhanced sensory feedback, termed osseoperception.[87] A review of 14 lower extremity OI studies noted consistent improvements in functional mobility, physical performance, and quality of life.[88] However, this technology is not without expense: the average cost of osseointegration surgery is approximately $55,000, with maintenance costs of approximately $2626 annually.[89]

Lower limb OI is not without risk, however. A percutaneous abutment extends from the distal end of the integrated intramedullary fixture. The skin-implant junction is at risk for infection, which may progress to osteomyelitis and necessitate implant removal. Reported infection rates range greatly, but they have been reported as high as 68%.[88] However, most infections are superficial and resolve with oral antibiotics, with reports of over 90% implant survivorship. Current efforts aim to achieve a stable chronic wound at the implant interface (Fig. 6). This is in contrast to early efforts that attempted to form a dermal seal through integration with textured implant surfaces, but these strategies were plagued by increased rates of infection.[37]

Several implant systems are commercially available worldwide; however, only the Osseointegrated Prostheses for the Rehabilitation of Amputees system has been approved for routine clinical use in the United States.

Fig. 6. (*Left*) A transfemoral amputee who was unable to tolerate a traditional prosthesis undergoes (*right*) osseointegration. A stable wound is achieved at the skin-implant junction.

CONCLUSIONS

Limb reconstruction aims to maximally restore function. The reconstructive algorithm continues to evolve as amputation techniques and prosthetic capabilities become increasingly sophisticated. A multidisciplinary approach is needed to appropriately identify the optimal treatment approach for each case. The goals of amputation are to achieve durable soft-tissue coverage over a stable skeletal construct and to preserve length and minimize pain. Early and intensive rehabilitation can maximize functional outcomes.

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