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Review

Review

Contemporary approach to soft-tissue reconstruction of the lower extremity after trauma

Matthew R. Zeiderman, MD and Lee L.Q. Pu, MD, PhD*

Division of Plastic & Reconstructive Surgery, Department of Surgery, University of California, Davis, Sacramento, CA, USA

***Correspondence. Email:** llpu@ucdavis.edu

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Abstract

The complex lower extremity wound is frequently encountered by orthopedic and plastic surgeons. Innovations in wound care, soft tissue coverage and surgical fixation techniques allow for improved functional outcomes in this patient population with highly morbid injuries. In this review, the principles of reconstruction of complex lower extremity traumatic wounds are outlined. These principles include appropriate initial evaluation of the patient and mangled extremity, as well as appropriate patient selection for limb salvage. The authors emphasize proper planning for reconstruction, timing of reconstruction and the importance of an understanding of the most appropriate reconstructive option. The role of different reconstructive and wound care modalities is discussed, notably negative pressure wound therapy and dermal substitutes. The role of pedicled flaps and microvascular free-tissue transfer are discussed, as are innovations in understanding of perforator anatomy and perforator flap surgery that have broadened the reconstruction surgeon's armamentarium. Finally, the importance of a multidisciplinary team is highlighted via the principle of the orthoplastic approach to management of complex lower extremity wounds. Upon completion of this review, the reader should have a thorough understanding of the principles of contemporary lower extremity reconstruction.

Key words: Lower extremity, Soft tissue, Reconstruction, Trauma, Surgical approach

Highlights

- Innovations in wound care, soft tissue coverage and surgical fixation techniques allow for improved functional outcomes after highly morbid injuries.
- Appropriate initial evaluation of the patient and mangled extremity, as well as appropriate patient selection for limb salvage are reviewed.
- The authors emphasize proper planning for reconstruction, timing of reconstruction and the importance of an understanding of the most appropriate reconstructive option.
- The importance of a multidisciplinary team is highlighted via the principle of the orthoplastic approach to management of complex lower extremity wounds.

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Background

The past 30 years have demonstrated much innovation in lower extremity reconstruction. Advances in wound management, microvascular free-tissue transfer and improved understanding of vascular anatomy has allowed surgeons to push the envelope when reconstructing the traumatized lower extremity [1, 2]. The addition of negative pressure wound therapy (NPWT) over the past 20 years has changed the management of complex lower extremity wounds, making soft-tissue coverage less of a limiting factor [2–4]. A multidisciplinary group of surgeons, infectious disease experts and rehabilitation specialists is often called upon at tertiary medical care centers to assist in the care of these highly morbid injuries. It is important for the reconstructive plastic surgeon or orthopedic surgeon to be familiar with the appropriate work-up and most recent innovations in the field to provide the patient with the best possible outcome. In this review, we outline the evaluation of the traumatic lower extremity patient, discuss the indications for reconstruction vs. amputation and the appropriate timeline, and review contemporary techniques in lower extremity soft-tissue reconstruction.

Review

Evaluation of traumatic lower extremity patient

A comprehensive approach to management of lower extremity trauma begins with appropriate patient selection. His or her medical condition must be carefully evaluated, particularly if there are other associated traumatic injuries. A thorough past medical and surgical history is essential to identify major surgical risks. Major risks include previous heart attack, stroke, poorly controlled diabetes, uncontrolled hypertension, hepatic or renal insufficiency, hypercoagulable state and peripheral arterial disease. A thorough physical exam of the neurovascular status to the extremity is essential.

Initial treatment includes debridement of contaminated and devitalized tissues, as well as fracture stabilization. Several debridements may be needed to achieve a clean wound bed. Bony injuries to be treated by the orthopedic traumatologist are identified and assessed with standard X-rays and computed tomography (CT) scans at the time of presentation. Leg perfusion should be assessed clinically. This can be done by physical examination and at the bedside with a handheld Doppler. Major vascular injury often occurs concurrently with severe limb injury. CT angiography (CTA) of the lower extremity or formal arteriogram should be considered when there is a large zone of injury which may include vessels for potential microvascular anastomosis [5]. CTA is less invasive than a formal arteriogram, but is limited in ability to assess directional flow as well as ability to assess vasospasm or local injury [6]. An arteriogram or color duplex ultrasound may be needed in these situations; both assess flow directionality and measure vessel caliber. Magnetic resonance angiography (MRA) is also an option for vascular imaging when the patient cannot tolerate iodinated contrast, but is time consuming and prone to scatter if metal is in the imaged field [7]. Where there is concern for venous injury or deep vein thrombosis, vein mapping should be performed prior to reconstructive efforts. Additional imaging modalities for perforator mapping and flap planning are discussed later in the article.

Indications for limb salvage *vs* amputation

The advent of microsurgical soft-tissue transfer has expanded indications for lower extremity salvage. Soft-tissue coverage is no longer a limiting factor. Limb salvage is indicated in severe limb trauma to a child, or healthy adults with intact sensation or expected return of function. A comprehensive evaluation of the patient's injury characteristics, age, medical co-morbidities, ultimate functional status and rehabilitation potential all weigh into the decision whether to pursue limb salvage or amputate. The need for amputation is life changing and disturbing to many patients. Acceptance may take time and careful counseling is needed. The decision should not be rushed. The Lower Extremity Assessment Project (LEAP), a multi-institutional prospective study of lower extremity trauma outcomes, demonstrated neither option has superior clinical outcomes [8, 9]. Both amputee and limb reconstruction patients have disappointing return to work proportions at 7 years post-injury (0.62 reconstruction, 0.47 amputation, 0.58 cumulative), a non-significant difference after adjustment, according to a LEAP study analysis by MacKenzie *et al.* [10]. A 2011 meta-analysis of 1138 patients (769 amputee, 369 reconstructions) by Akula *et al.* found that limb salvage is more psychologically acceptable to patients than amputation, but physical outcomes are similar following amputation [11]. This meta-analysis utilized the validated quality-of-life outcomes scoring systems including the Short Form-36 (SF-36) and Sickness Impact Profile (SIP). Notably, mean psychological SIP scores were 15.6 and 11.5 for amputation and reconstruction, respectively ($p = 0.05$). Mean physical SIP scores were 16.2 and 13.3 for amputation and reconstruction, respectively (NS). More recent studies of the US military population in the Afghanistan and Iraq wars have also looked into these differences [12]. The authors found that early amputation was generally associated with similar or fewer adverse health outcomes relative to late amputation or limb salvage. Notably, patient undergoing late amputation had high rates of adverse psychological and physical outcomes. The 2013 Military Extremity Trauma Amputation/Limb Salvage (METALS) study looked at similar outcomes using the Short Musculoskeletal Function Assessment (SMFA) [13]. The authors found that on regression analysis, patients who underwent amputation reported significantly lower scores (better functioning) in all domains of the SMFA compared with patients with limb salvage ($p < 0.01$). The most recent data comes from a 2017 study of Dutch Armed Forces service members injured in Afghanistan which found amputees had more favorable outcomes regarding pain and physical well-being compared to limb salvage patients as measured by the SF-36 and EuroQol-6D (EQ-6D) [14].

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Results in the military population may not be generalizable to the civilian trauma population given the mechanism of injury as well as access to prosthetists and rehabilitation specialists, so results should be interpreted cautiously. Finally, while cost should not determine if a limb is to be salvaged or amputated, one economic model developed by Chung *et al.* found the life-time cost of limb salvage to be lower than that of amputation, particularly with a long projected lifetime [15]. Limb salvage patients also had overall utility weights, 0.969 for salvage and 0.954 for amputation, including adjusting and accounting for complications. McKenzie *et al.* had similar findings [16]. Patients undergoing amputation for lower extremity trauma had slightly higher but similar health care costs at 2 years at $91 106 compared to $81 316 for limb salvage patients. Projected lifetime health care costs for amputees were estimated to be 3x higher than limb salvage patients at $509 275 *vs* $163 282, respectively. Much of the cost difference is attributed to prosthesis maintenance and replacement. However, as the authors note, these findings remain subject to bias of patient reports as well as selection bias of patient preferences and injury severity.

Classically, an insensate foot due to tibial nerve injury was a contraindication to limb salvage, though there was a lack of evidence to support this practice [17]. There is an important distinction between tibial nerve dysfunction (neuropraxia, reversible ischemia) and transection or permanent injury. As part of the LEAP study, Bosse *et al* in 2005 found no significant difference in functional outcomes between limb salvage or amputation among patients with an insensate foot at the time reconstruction compared to matched controls, with the important exception that patients who underwent amputation had increased difficulty using stairs [18]. An equal proportion (55%) of patients in insensate salvage and insensate control groups reported or tested as having normal plantar sensation at 14 months post-injury. Visual examination of tibial nerve continuity is often not possible, making nerve dysfunction and disruption difficult to assess. This suggests surgeons should not dogmatically encourage amputation when a patient initially presents with absent plantar sensation.

In 1985 Lange *et al.* suggested reasonable criteria for salvage *vs* amputation [19] (Table 1). Indications for amputation include crush injury with prolonged warm ischemia (>6 h) or tibial nerve transection. Relative indications include polytrauma, severe ipsilateral foot trauma or projected long recovery course. Given the findings of Bosse *et al.* we would recommend nerve injury only be included if transection is verified (Table 1) [18].

Timing of soft-tissue reconstruction

Timing of definitive soft-tissue reconstruction of lower extremity trauma is determined by many factors, including patient condition, wound condition, fracture type and exposed structures [20]. Exposed structures and infection risk are important to consider. Surgeons strive for prompt bony stabilization and soft-tissue reconstruction. More important than simply achieving soft-tissue coverage is obtaining a clean wound free of contaminated and devitalized tissue that will inhibit healing [21–23]. Aggressive debridement to healthy bleeding tissue is essential. If needed, additional imaging modalities such as indocyanine green (ICG) fluorescence angiography (discussed later) can be used as an adjunct to assess tissue perfusion and guide debridement. Necrotic bone does not heal and serves as a nidus for infection. Multiple debridements are often necessary. Adequate time for complete demarcation of the zone of injury must be allowed, which will vary by patient and mechanism [24]. However, the sooner the wound is clean, the sooner it can be reconstructed with lower risk of infection.

The work of Marko Godina in 1986 suggested that microvascular soft-tissue coverage of open extremity fractures should be performed within 72 h of injury to maximize free-flap success rate [25]. A time of 72 h is posited to be prior to the onset of significant bacterial colonization and fibrosis, which complicates microvascular dissection and anastomosis. For years soft-tissue coverage within 72 h of injury was considered 'gold standard,' but there is no consensus and timing remains debated. Byrd *et al.* [26]advocated definitive soft-tissue coverage within 5 days, and Yaremchuk *et al.* recommended definitive soft-tissue coverage be performed 7–14 days after injury to allow time for adequate debridement [24]. Contemporary studies suggest successful reconstruction can be performed well beyond the 72 h window [27–31].

The advancement of orthopedic fixation techniques, expanded use of antibiotic impregnated cement, antibiotic beads and introduction of NPWT has extended the window for soft-tissue reconstruction, liberalizing constraints of the 72-h period [31]. Given these advances, there is a limited role for the emergency free flap to the lower extremity. Average time to soft-tissue reconstruction increased from 6.12 to 12.5 days from 2002 to 2011 [32]. This increase may be attributable to NPWT, which has allowed extending the interval to coverage without adverse effects, decreased rates of infection and may decrease rates of flap reconstruction [33–36]. Recent studies suggest the ideal period for early reconstruction can be extended to 10–14 days without adverse effect on outcomes [30, 31, 37]. In the absence of definitive guidelines, the authors suggest reconstruction as soon as possible when the patient is medically optimized and the wound clean, preferably within 2 weeks of injury. A list and brief summary of the pertinent literature on the timing of lower extremity trauma soft-tissue coverage is provided in Table 2 [25–30, 36–43].

Trend of reconstruction

When treating complex lower extremity wounds, the goal is to provide reliable soft-tissue coverage with optimal cosmesis while minimizing morbidity. Advancements in wound care technology such as NPWT, hydrosurgical debridement devices like Versajet (Smith & Nephew, Watford England)

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Table 1. Indications for limb salvage *vs* amputation of the traumatized lower extremity

Indications for limb salvage	Indications for amputation
• Young patient • No ischemia or tibial nerve injury • Good rehabilitation potential	Absolute • Complete disruption of posterior tibial nerve • Crush injury with ischemia time > 6 h Relative • Severe polytrauma with life-threatening injuries • Severe ipsilateral foot trauma • Anticipated protracted reconstruction and recovery • Segmental tibia fracture

Table 2. Pertinent literature regarding time to definitive soft-tissue coverage of lower extremity trauma

Article	Year	Patients No.	VAC	Time to definitive soft-tissue coverage	Findings
Byrd *et al*. [26]	1981	18	No	48–72 h ≤5 d	• Mean 4 months to bony union • Several patients with IIIA wounds excluded for coverage beyond 5 d
Godina [25]	1986	532	No	<72 h 72 h–3 months >3 months	• <72 h: Decreased flap loss (0.75 *vs* 12 *vs* 9.5%) and mean time to bony union (6.8 *vs* 29 *vs* 14 months) and decreased infection rates (1.5 *vs* 17.5 *vs* 6%)
Khouri and Shaw [39]	1989	260	No	Immediate 1 d–1 week 1 week–2 months 2 months–1 year >1 year	• Similar rates of flap loss, highest in 2 months 1 y (16%) • 35% Primary wound healing 1 d—1 week, 65% additional soft-tissue loss or infection requiring additional procedures • 85 Patients with >1 year follow-up, 91% 'normal leg function' • Chronic osteomyelitis not documented
Rinker *et al*. [36]	2008	105	Yes 22%	1–7 d 8–42 d >42 d	• No significant difference in osteomyelitis or flap-related complications, but trends toward higher rates in 8–42 d group • Time to bony union significantly shorter in 1–7 d group (4.2 *vs* 6.5 *vs* 6.2 months) • Subacute patients with VAC significantly lower rates of overall complications (35 *vs* 53%), infections (6 *vs* 18%) and flap-related complications (12 *vs* 21%) • 8–42 d time to bony union significantly shorter with VAC (4.9 *vs* 7.2 months)
Starnes-Roubaud *et al*. [28]	2015	100	Yes (% not documented)	<15 d >15 d	• No significant difference in time to bone union, rates of chronic osteomyelitis, or free-flap failure • ≤4 reconstructive procedures significantly increased rate of delayed or nonunion
Lee *et al*. [30]	2019	358	Yes 'routine use' 1996–2016	< 72 h 4–90 d 4–9 d *vs* 10–90 d subgroup analysis >90 d	• <72 h Superior outcomes *vs* 4–90 d • Rates flap failure, major complications • Multivariate analysis-no significant difference in total or partial flap failure, take-backs-overall complications for <72 h *vs* 4–9 d • 4–9 d *vs* 10–90 d significantly lower • Flap success decreases beginning post-injury day 10 • Early reconstructive window safely extended to within 10 d

VAC vacuum-assisted closure

and pulsed lavage irrigation systems, and advances in vascular anatomy understanding have allowed increased use of local and regional flaps, notably perforator flaps, in localized zones of injury. The introduction of NPWT and acellular dermal matrices like Integra allows surgeons to achieve thin, reliable soft-tissue coverage of appropriately selected wounds that once required a flap through less invasive surgical methods. These innovations have shifted the senior author's reconstructive algorithm to favor local flaps and dermal matrices with skin grafts over free-tissue transfer when wound size is amenable, reserving free flaps for large, extensive wounds or as a back-up. In the absence of fracture or exposed nerve

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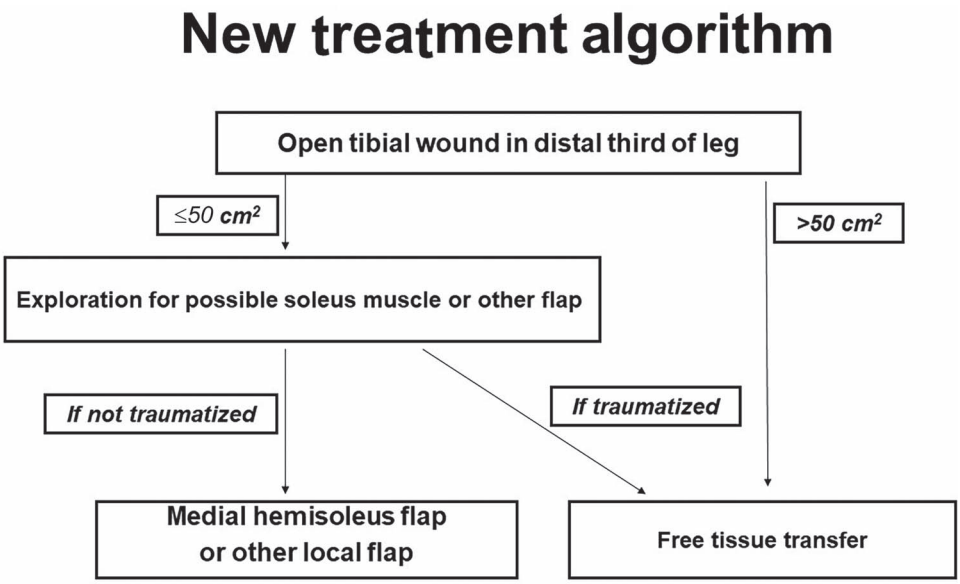


Figure 1. Suggested algorithm for selection of soft-tissue reconstruction of tibial fractures of the distal third of the leg

or vessel, use of NPWT and wound care adjuncts often provide a good result. Free-tissue transfer is an essential component of limb salvage, classically reserved for defects of the distal third of the tibia, foot and ankle. Free flaps for lower extremity salvage are performed faster and safer than decades ago. Sometimes, a free fasciocutaneous flap provides the most aesthetically pleasing reconstruction. While free-tissue transfer has become the preferred reconstructive method for many surgeons treating lower extremity trauma, the senior author's preference is to reserve free-tissue transfer as a back-up for when local options are unavailable, there is composite tissue loss, or when wounds are too extensive for local coverage options, particularly in the distal third or large defects around the knee. If there is a viable, reliable local flap option, it should be used first. The senior author's algorithm for management of wounds in the distal third of the leg is demonstrated in Figure 1. With the introduction of the perforasome concept and improved understanding of perforator anatomy, local fasciocutaneous flaps (named or 'free-style') can be reliably utilized with low donor-site morbidity, replacing 'like with like,' and less-intensive postoperative monitoring than free-flaps [44, 45]. Lower-extremity reconstruction with free-tissue transfer now has success rates >90% in many centers, but still carries the risk of flap loss and partial loss [5,28,46, 47]. A study by Wettstein *et al.* reported 13% partial flap loss in 197 free flaps, and Sofiadellis *et al.* reported an 11.4% partial flap loss rate [48, 49]. While unknown if flap loss occurred over critical structures, such complications may require another anesthetic for debridement or additional soft-tissue coverage, possibly another free-flap. Free-tissue transfer has evolved and become a work horse for lower extremity reconstruction. However, the use of local reconstructions combined with NPWT, other wound care adjuncts and local flaps or dermal matrices should not be overlooked in an era of advanced microsurgery [4, 50].

The role of NPWT

The widespread use of NPWT has proven to be an essential therapeutic advancement for the temporization of definitive soft-tissue coverage. The acceptance of this modality has been widespread for many reasons. Use is straightforward, and it requires change every 48 h as opposed to two or three daily gauze dressing changes. A black polyurethane sponge is applied to the wound, sealed, and a negative pressure of 75–125 mmHg is applied. Occasionally a white polyvinyl alcohol sponge is used over areas where sponge adherence is less desired, such as exposed bone or tendon devoid of peritenon. A piece of petroleum gauze could also be placed between exposed bone or tendon and a black sponge. On rare occasion, white foam is placed over an exposed vessel with an interposed contact later, such as petroleum gauze. Prolonged NPWT use can devitalize and desiccate bone and tendon, and should be avoided [31]. Negative pressure wound therapy is hypothesized to facilitate wound bed optimization by minimizing edema, reducing wound surface area and increasing perfusion of granulation tissue via reduced capillary afterload with associated decrease of bacterial colonization [51–53]. These physiologic benefits are thought to oppose edema, inflammation and tissue fibrosis that complicate microvascular reconstruction.

Negative pressure wound therapy has increased the window within which acute reconstructions can be successfully performed with acceptable results, allowing for management of life-threatening injuries, optimization of patient condition, nutrition, wound bed quality and optimal reconstructive strategy. However, basic principles of thorough debridement and bony stabilization remain essential for limb salvage,

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and NPWT availability does not compensate for inadequate debridement [22]. Godina did not have the benefit of NPWT, and his recommendations to perform soft-tissue coverage within 72 h of injury should be interpreted in that context. The introduction of NPWT has extended the time to definitive soft-tissue coverage beyond the dogmatic 72 h to weeks or even months. Lee *et al*. recently demonstrated no increase in flap failures or complications for flaps performed 4 to 9 days after reconstruction versus those within 72 hours of injury [30]. The authors suggest these benefits are due to NPWT. Raju *et al.* reported that with adequate debridement and proper flap selection, NPWT allows the window of successful reconstruction to be extended to several weeks, with favorable 96% flap survival rate and 8% infection rate [54]. Rinker *et al.* reported that patients treated with NPWT who underwent flap reconstruction within a subacute period of 8–42 days had significantly lower rates of overall complications (35%), infections (6%) and flap-related complications (12%) compared to those with conventional dressings (53, 18 and 21%, respectively) ($p < 0.05$) [36]. A 2015 metanalysis by Schlatterer *et al.* found lower infection rates with treatment by NPWT compared to conventional dressings from pooled randomized controlled trials (OR 0.17, 95% CI [0.09, 0.32], $p < 0.00001$) and retrospective cohort studies (OR 0.26, 95% CI [0.16, 0.12], $p < 0.00001$) [34]. However, other studies have suggested higher rates of wound infection with the use of NPWT and delays in coverage [43, 55]. Liu *et al.* found a trend toward higher rates of osteomyelitis for patients treated with NPWT undergoing soft-tissue reconstruction >7 days after injury compared to <72 h (26.2 vs. 12.5%, $p = 0.09$) [43]. Multivariate analysis demonstrated that delayed free-tissue transfer beyond 14 days independently predicted higher rates of flap take-backs (OR = 7.41, 95% CI = 1.56–35.18), deep metal infection (OR = 10.53, 95% CI = 1.11–99.83) and osteomyelitis (OR = 11.50, 95% CI = 1.19–111.51). Bhattacharyya *et al.* found a >36% infection rate in lower extremity trauma patients undergoing reconstruction treated with NPWT [55]. However, it should be noted that infection rate for reconstruction after 7 days of injury was 57%, while less than 7 days after injury it was only 12%. The authors would suggest that the reasons for discrepancies between studies are multifactorial, and wound cleanliness and bacterial burden at the time of NPWT application as well as wound care regimen largely influence these findings. Over-reliance on NPWT may lead to complications. Soft-tissue coverage of open fractures should be provided as soon as possible.

One of the over-looked benefits of NPWT is decreased reconstructive complexity. This has been demonstrated by the previously cited experience of Parrett *et al.* [4]. Decreased tissue edema with enhanced blood flow and granulation tissue makes more wounds amenable to local and regional flaps, or even reconstruction with skin substitute scaffolds or skin graft [54, 56]. This is important for centers with limited free-tissue transfer capability or experience, but prolonging time to reconstruction must be balanced with infection risk [56].

The role of Integra

The introduction of xenograft skin substitute scaffolds, otherwise known as acellular dermal matrices, has expanded reconstructive options. Products such as the Integra bilayer wound matrix (Integra Lifesciences, Plainsboro, NJ) have demonstrated satisfactory outcomes in lower extremity reconstruction, particularly for coverage of small areas of exposed bone and tendon that require only a thin layer of soft-tissue coverage [57, 58]. Integra is neovascularized over the course of 2–4 weeks, forming a neodermis without relying on imbibition like a skin graft. When combined with NPWT, the vascularization process can be shortened [58, 59]. The neodermis is subsequently skin grafted after adequate neovascularization occurs and removal of the superficial silicone sheet layer.

Integra can be used to effectively cover tendon and bone, respectively, with surrounding granulation tissue. However, only small defects of bone or tendon devoid of periosteum or peritenon will neovascularize the graft [57, 60]. A good range of motion and tendon glide has been demonstrated with Integra [61]. A disadvantage of Integra is that a second operation for skin grafting is often needed. However, this can be performed on an outpatient basis, and some authors describe a single-stage procedure with Integra or related matrices and concurrent split thickness skin graft [61,62].

Dermal matrices like Integra provide ease of use, rapid application, have unrestricted wound size and have no donor-site morbidity. The authors believe that Integra and other dermal matrices should primarily be used as an alternative reconstructive option for select patients with peripheral vascular disease, severe diabetes or other comorbidities where local flaps are not available. It is also appropriate when the patient is a poor candidate for free-tissue transfer and prolonged anesthesia, or when microvascular surgical services are not available [3]. However, dermal matrices are an excellent option in the appropriately selected patient (Figure 2).

The role of local flaps

Local flaps, such as an adjacent muscle like the gastrocnemius or soleus, remain the workhorses of lower extremity reconstruction. A local flap is a good option for definitive reconstruction of smaller wounds with exposed bone, tendon or hardware. Local flaps can be muscle, fasciocutaneous or adipofascial. A thorough surgical exploration should be done prior to flap selection to ensure the local tissue is outside the zone of injury. Hemorrhagic or swollen local muscle indicates unusable tissue and need for a more distant regional flap or microvascular free-tissue transfer [3].

The gastrocnemius muscle flap is a good local choice for knee and proximal tibia defects. Either the medial or lateral gastrocnemius can be chosen. The larger medial gastrocnemius is best for knee and proximal tibia defects. The lateral gastrocnemius is best for lateral knee and fibula defects. Arc of motion can be increased by scoring the fascia of the

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Figure 2. A 4-year-old male had (**a**) a degloving injury to his right medial foot and ankle with a 12 x 6 cm open wound and exposed bone. (**b**) Good 'skin graftable' wound base at 2 weeks after conservative management with Integra and NPWT. (**c**) Results at 7 months follow-up after a subsequent skin grafting procedure



Figure 3. A 59-year-old male had (**a**) a 20 x 11 cm open fracture wound over his right leg with exposed distal tibial fracture site. (**b**) The immediate result after a proximally based medial hemi-soleus muscle flap and split-thickness skin grafts for his wound coverage. (**c**) Results at 5 months follow-up after the above reconstructive procedures

muscle belly or division of the muscle origin from the femoral condyle.

The soleus muscle flap is a good choice for middle-third tibial defects, as well as defects in the junction of the proximal and middle third or middle and distal third [63–65]. The medial hemisoleus flap can be used to successfully cover many middle-third wounds if the defect is not too large, usually <50 cm^2 if approaching the distal third [64]. Small distal third tibia wounds can be covered with a reverse hemisoleus flap [63, 65, 66]. If the muscle is traumatized, microvascular free-tissue transfer will be necessary (Figure 3). Caution is urged if planning to use the reverse hemisoleus flap in a patient with peripheral vascular disease or severe diabetes. Impaired flow to the posterior tibial artery or small vessel disease of perforators may compromise flap viability. Combined medial gastrocnemius and medial hemisoleus muscle flaps can used together to cover large or extensive middle-third tibia wounds [67, 68]. The use of multiple local muscle flaps for lower extremity reconstruction has been overshadowed by microvascular free-tissue transfer. However, advantages of multiple local muscle flaps include shorter operative time, straightforward technique, shorter hospital stay, less intensive flap monitoring, less vigorous postoperative care and no additional soft-tissue debulking [68].

The tibialis anterior muscle flap is less commonly used but simple and effective for small soft-tissue defects. The flap can be used for small soft-tissue defects of the middle and distal third [69].

The role of regional flaps

Regional flaps are pedicled flaps with a more distant blood supply or donor vessel than local flaps. Commonly used regional flaps include the distally based (reverse) sural fasciocutaneous flap and the posterior tibial artery perforator flap. The reverse sural fasciocutaneous flap has demonstrated reliability and versatility in coverage of wounds of the distal tibia, as well as the heel and medial and lateral malleoli [3, 70–73]. This flap can be raised as an adipofascial flap as well, though the senior author does not favor this technique in females, whom he has observed to have a poorly defined fascial layer in this area [74, 75]. The patient must have a patent peroneal artery with identifiable perforators using Doppler.

The posterior tibial (PT) artery perforator flap is a pedicled fasciocutaneous or adipofascial flap well suited for wounds of the anterior and medial distal leg, as well as the achilles tendon [76, 77]. These are usually small flaps, fashioned over a suitable perforator identified with Doppler [77].

For wounds of the foot, several fasciocutaneous flaps can be selected for relatively small wounds. The dorsalis pedis (DP) flap can be raised as an adipofascial, myocutaneous or fasciocutaneous axial flap from the dorsal foot, supplied by the DP artery. It is best for wounds of the distal tibia, ankle, medial sole, ankle or heel. The reverse sural is much more commonly used for wounds of the heel. Flow through the anterior tibial and DP arteries must be verified. The medial plantar artery flap can also be used for defects of the foot and ankle [78]. PT and DP artery patency must be confirmed prior to use.

Finally, as previously discussed, introduction of the perforasome concept and improved understanding of perforator anatomy has introduced the possibility of 'free-style' local fasciocutaneous flaps, in addition to the named flaps just discussed. Local 'free-style' flaps can be reliably utilized with

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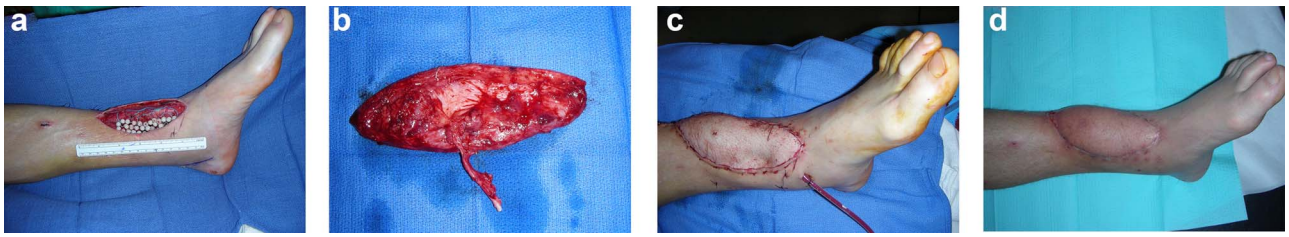


Figure 4. A 54-year-old male had (**a**) a 12 x 6 cm open fracture wound over his left distal third of the leg with exposed distal tibial fracture site. (**b**) A free ALT flap was harvested from his right thigh. (**c**) The immediate result after a free ALT flap transfer to his left distal leg. (**d**) Results at 2 months follow-up after above reconstructive procedure

low donor-site morbidity, providing nice tissue match and replacing 'like with like' [44, 45].

The role of free flaps

Refinements and innovations in microvascular free-tissue transfer over past decades has made free flap reconstruction a reliable and often the best option, particularly in wounds of the distal third of the tibia and foot with exposed bone, joint, neurovascular bundle, tendon or hardware. Free-tissue transfer may also be required for large wounds around the knee or proximal or middle leg [79, 80]. Microvascular free-tissue transfer requires skilled microsurgeons with sophisticated perioperative care. Microvascular services are frequently unavailable at community hospitals in the USA. Patients requiring complex lower extremity reconstruction usually require treatment at a university-based tertiary care hospital.

When planning microvascular free-tissue transfer, special attention must be paid to the peripheral vascular system and planned recipient vessels. Recipient vessels should be outside the zone of injury. Conventional practice recommends the use of vessels proximal to the wound due to increased vessel caliber, but recipient vessels distal to the zone of injury can be used without increased complication rates [81, 82]. Vessel choice should be based upon vessel quality and ease of access.

Flap selection is based on several criteria. The most important considerations include soft-tissue requirement, donor-site availability, and pedicle length and diameter. Classically, in North America free muscle flaps including the latissimus dorsi, rectus abdominis and gracilis were preferred. For many years North American surgeons avoided fasciocutaneous perforator flaps in favor of muscle flaps due to the need for debulking the generally thicker tissue, favoring a better contoured muscle flap after denervation atrophy. However, recent years have demonstrated a shift toward fasciocutaneous perforator flaps as the primary choice due to comparable functional and reconstructive outcomes with decreased donor-site morbidity [46, 83]. Most importantly, fasciocutaneous flaps prove to be equally effective as muscle flaps at clearing infection and providing stable wound coverage [84].

Fasciocutaneous perforator flaps spare functional muscle units. This decreases donor-site morbidity, which is particularly important in the trauma population. In weight-bearing areas, fasciocutaneous flaps are more resistant to breakdown and shear than muscle flaps [85]. Fasciocutaneous flaps are also easier to re-elevate for hardware revision or bone grafting, if needed. The anterolateral thigh (ALT) free flap has become a workhorse flap and is the most commonly used perforator flap in the senior author's practice and for many around the world [86] (Figure 4). Other fasciocutaneous perforator flaps can be selected based upon surgeon preference and familiarity. Other commonly used flaps include the superficial circumflex iliac perforator (SCIP), thoracodorsal artery perforator (TDAP), deep inferior epigastric artery perforator (DIEP) and 'free-style' perforator flaps [87–89]. Traditional muscle flaps such as the latissimus dorsi, rectus abdominis and gracilis remain acceptable choices.

When performing perforator flap surgery, it is the senior author's preference to pre-operatively identify suitable perforators with color duplex ultrasonography because it is cheap, easily available, non-invasive, and can evaluate vessel size and course [90–92]. Perforator identification is also commonly performed with handheld pencil Doppler ultrasound, pre-operative CT angiography and intraoperative ICG angiography [93]. Angiography of the lower extremities can be performed with helical CT or multidetector computed tomography (MDCT). MDCT acquires thin slices, in less time, with less radiation exposure and higher resolution than helical CT [7]. MDCT collects information on volume and can be reconstructed as a 3D image, creating a 3D vessel map. Important, one study demonstrated MDCT has a 70% sensitivity and 100% positive predictive value (PPV) for detecting perforators, and Doppler flowmetry has 100% sensitivity and 80% PPV in identifying perforators [93]. Preoperative perforator identification increases operative efficiency and shortens the learning curve for raising perforator flaps with variable anatomy. The role of ICG angiography in both free and pedicled flap dissection is primarily for intraoperative verification of perforator adequacy and flap perfusion, particularly in larger flaps. This helps the surgeon to make reliable judgments of flap perfusion and reaffirm clinical judgment, thereby reducing partial flap necrosis, fat necrosis and thus complications [94].

The role of orthoplastic approach for complex injuries

The patient with complex lower extremity trauma requires both bony and soft-tissue reconstruction. Successful management requires the collaboration of both orthopedic and plastic surgeons, termed the orthoplastic approach, as well

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as early involvement of infectious disease specialists [20, 95]. The combined optimization of bony reconstruction, a complimentary soft-tissue reconstruction and early infection management will yield the optimal result for the mangled extremity. Further, the orthoplastic approach can successfully complete both bony and soft-tissue reconstruction in a single stage [3, 96]. An example might be a contralateral osteocutaneous fibula free flap for a tibial wound with composite bone and soft-tissue loss.

Reconstruction for composite defects

Management of the lower extremity wound with composite bone and soft-tissue loss can be quite challenging. As mentioned previously, this is often best treated with an orthoplastic approach. Following fracture or debridement of chronic osteomyelitis with bone loss, patients often require reliable soft-tissue coverage of the bony defect, followed by subsequent autologous bone graft at a later procedure. Bone defects >6 cm are best treated with vascularized bone graft, such as microvascular free fibula, iliac crest or, rarely, rib transfers [20, 96]. The best method of bony reconstruction of the lower extremity remains debated. Some surgeons prefer autologous bone graft, others bone graft substitute, and some bone transport (Ilizarov technique) [97]. All methods can provide successful bony reconstruction in the properly selected patient. It is the senior author's opinion that a vascularized free bone graft is the best option for large bone defects of the distal tibia. Regardless of method chosen, it must be reiterated that successful reconstruction of composite defects requires a stable soft-tissue envelope to allow for bony union.

New research and advancement in lower extremity reconstruction

Most advancements in lower extremity reconstruction focus on the use of both free and pedicled perforator flaps [98, 99]. The angiosome concept described by the landmark anatomical Taylor and Palmer study in 1987 described the major perforating vessels in the body and their interconnections [100]. Further research refined our understanding of the vascular territory supplied by individual perforators, termed perforasome theory [98]. Subsequent years of study and clinical practice have demonstrated the great utility of traditional perforator flaps for microvascular free-tissue transfer, as well as 'free-style' free flaps and pedicled flaps not based on a named vessel, but instead on 'hot zones' where reliable perforators can be identified [45, 86, 87, 99, 101–103].

Supermicrosurgery, defined as a pedicled <0.8 mm diameter, has been pioneered in lower extremity reconstruction by Hong with good success [104]. Supermicrosurgery flap survival rates of 95–98% are reported for the lower extremity, comparable to 'traditional' microsurgical perforator flaps [104, 105]. The number of possible donor sites based on a single perforator is increased, concurrently decreasing donor-site morbidity. However, great microsurgical skill is needed, and the learning curve is steep [104]. Finally, pre-expanded perforator flaps are yet another innovative idea with applications in reconstructive surgery. While applications are primarily focused on the face and neck, they can be used to reconstruct defects of the lower extremity as well, particularly when resurfacing of large areas with thin tissue is needed [106, 107].

Finally, the past decade has seen increasing usage of ICG fluorescent dye with near infrared imaging as an adjunct to assess skin flap viability. It has been used across numerous specialties to evaluate vascular perfusion and lymphatic drainage [85, 108]. It now has applications as a useful tool to assess perforator perfusion distribution for flap design, and has also demonstrated efficacy as an adjunct to guide debridement in Gustilo IIIB lower extremity fractures [109, 110].

Conclusions

There are numerous important reconstructive principles outlined in this review. These include proper initial wound evaluation, preparation and understanding of the optimal reconstructive option. The reconstructive surgeon should embrace the orthoplastic approach to lower extremity reconstruction for management of complex composite tissue defects and become skillful in contemporary perforator flap techniques. With good surgical skill and judgement, optimal patient outcomes can be expected.

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Consent for publication

All patients provided written informed consent for publication of pictures and personal data.

Conflicts of interest

The authors declare that they have no competing interests.

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