Principles of Orthoplastic Surgery for Lower Extremity Reconstruction: Why Is This Important?

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Abstract

Background Regardless of the antecedent etiology, lower extremity salvage and reconstruction attempts to avoid amputation, restore limb function, and improve quality of life outcomes. This goal requires a treatment team well versed in neurovascular pathology, skeletal and soft tissue reconstruction, and physical rehabilitation.

Methods A review was performed of historical milestones that lead to the development of orthoplastic extremity reconstruction, principles of current management and the evidence that supports an orthoplastic approach. Based on available evidence and expert opinion, the authors further sought to provide insight into the future of the field centered around the importance of a multidisciplinary management protocol.

Results Historically, orthopaedic and plastic surgeons worked separately when faced with challenging reconstructive cases involving lower extremity skeletal and soft tissue reconstruction. With time, many embraced that their seemingly separate skill-sets and knowledge could be unified in a collaborative orthoplastic approach in order to offer patients the best possible chance for success. First coined by the senior author (LSL) in the early 1990s, the collaborative orthoplastic approach between orthopaedic and plastic surgeons in limb salvage for the past several decades has resulted in a unique field of reconstructive surgery. Benefits of the orthoplastic approach include decreased time to definitive skeletal stabilization/soft tissue coverage, length of hospital stay, post-operative complications, need for revision procedures and improved functional outcomes.

Conclusion The orthoplastic approach to lower extremity reconstruction is a collaborative model of orthopaedic and plastic surgeons working together to expedite and optimize care of patients in need of lower extremity reconstruction. The implementation of protocols, systems, and centers that foster this approach leads to improve outcomes for these patients. We encourage centers to embrace the orthoplastic approach when considering limb salvage, as the decision to amputate is irreversible.

Keywords
- lower extremity
- reconstruction
- orthoplastic
- flap
- free flap

Regardless of the antecedent etiology, lower extremity salvage and reconstruction attempts to avoid amputation, restore limb function, and ideally improve quality of life outcomes.[1] This goal requires a treatment team well versed in neurovascular pathology, skeletal and soft tissue reconstruction, and physical rehabilitation. Historically, orthopaedic and plastic surgeons worked separately when faced with challenging reconstructive cases involving lower extremity skeletal and soft tissue reconstruction. With time, many embraced that their seemingly separate skill-sets and knowledge could be unified in a

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collaborative orthoplastic approach to offer patients the best possible chance for success. Beyond the concerted care of orthopedic and plastic surgeons, limb salvage today benefits from input from many other specialties including musculoskeletal radiologists, vascular surgeons, infectious disease specialists, physical therapists, prosthetists, and specialized nursing staff.[2] Accordingly, the authors sought to review historical milestones that lead to the development of orthoplastic extremity reconstruction, summarize current treatment methods, and provide insight into the future of the field centered around the importance of a multidisciplinary management protocol.

Historical Milestones that Allowed for the Development of Orthoplastic Surgery

The evolution of lower extremity reconstruction has been driven by the paramount importance of bipedal ambulation in normal activities of daily living. Early clinical observations of bone and soft tissue factors associated with restoration of limb function laid the foundation for the complex reconstructive procedures we are capable of performing today. During the time of Hippocrates nearly 2,500 years ago, fractures were stabilized with splints or external fixation while soft tissue wounds were treated with ointments and potions. Hippocrates also described therapeutic amputation for vascular gangrene and healing by secondary intention. Four centuries later, Celsus emphasized the need for early debridement of a wound, removal of foreign bodies, and hemostasis. In the mid-16th century, Ambroise Paré, a French surgeon considered one of the fathers of surgery, described the continuing pain of an amputated limb, so-called phantom limb. Pain continues to be a driver of discussion when considering early amputation and prosthetic fitting or complex limb salvage. The first indications for amputation were published in Benjamin Bell's book "A System of Surgery" in 1796.[3] These included "bad" compound fractures or deformity and extensive lacerations/contusions. Bell also recognized different indications for military and civilian trauma because of better access to care and decreased violence in the latter, which continues to affect disparities in outcomes between these two groups today.

In 1846, Robert Liston, a Scottish surgeon (1794–1847), performed the first operation in Europe under ether anesthesia, an amputation for tibial osteomyelitis. His student who witnessed the surgery, Joseph Lister (1883–1897), a British surgeon and pioneer in aseptic surgery, was displeased with patient outcomes following lower extremity fractures. In an 1867 Lancet publication, he reported on a series of 11 patients with compound tibial fractures, none of whom suffered septic complications—these findings were unprecedented at the time.[4] Lister also introduced the use of silver wires for internal fixation in 1877. It was becoming evident that modifications to traditional ways of lower extremity treatment would have significant implications for improving patient outcomes.

The Gross Clinic is perhaps one of the most famous American paintings ever made. Depicted in the painting, Samuel Gross (1805–1884) treated a young man for osteomyelitis of the femur with a conservative operation as opposed to an amputation, which had been the primary treatment method in the previous decades.[5] The Gross Clinic was more than just a painting; for perhaps the first time in history, surgery emerged as a healing profession. Thomas Huntington (1849–1929) was also well known for his contributions to aseptic surgery as well as the treatment of fractures. In 1905, he was the first to perform a pedicled vascularized fibula to reconstruct the defect that followed radical debridement of tibial shaft osteomyelitis.[6]

Perhaps the first orthopaedic and plastic surgery collaboration was between Sir Harold Gillies (1882–1960) and Sir W. Arbuthnot Lane (1856–1943). Sir Harold Gillies is widely accepted as the father of modern plastic and reconstructive surgery. Sir W. Arbuthnot Lane (1856–1943), a skilled orthopaedic, cleft lip and general surgeon made "internal fixation" practical by introducing metal plates and bone screws in 1909. In referencing his appointment of Gillies to Sidcup during World War I, Lane stated that he wanted to make that center one of the biggest and most important for plastic work in the world. Many believe the orthoplastic discipline origins trace back to their close interactions and complimentary skill-sets in treating wounded soldiers in World War I.

Countless advancements were made in vascularized bone, soft tissue flap, and microsurgical techniques later in the 20th century. In 1946, W.J. Stark, an orthopaedic surgeon, described the first pedicled muscle flap to treat lower extremity osteomyelitis, and when used with antibiotics, had double the success rate compared with no flap coverage.[7] In the late 1950s, Dr. Harry Buncke (1922–2008) demonstrated successful replantation and transfer of tissues perfused by 1-mm vessels. Around the same time, Julius Jacobsen and his student, Ernesto Suarez, found themselves dissatisfied with the magnification offered by surgical loupes. They introduced the operating microscope for small vessel anastomosis in 1960. In 1973, Rollin Daniel and G. Ian Taylor reported the first free groin flap transfer to cover a lower extremity soft tissue defect. In 1975, G. Ian Taylor, described the first use of a free vascularized fibula for large segmental bone defects, which added yet another tool for the reconstructive surgeon. In an article that they coauthored, Daniel and Taylor opened by referencing Harry Buncke: "The successful transplantation of a block of composite tissue by reanastomosing the microvascular pedicle has untold experimental and clinical possibilities."[8] The clinical impact of these historical milestones would soon be appreciated in the years that followed.

Composite vascularized tissue transfers became commonplace in the 1980s. Marko Godina (1943–1986) played a major role in the advances made in reconstructive microsurgery during this time.[9,10] In 1986, the year of his passing, he described the pathophysiology of high-energy trauma and advocated for radical debridement and early tissue coverage within the first 3 days of injury.[11] He also supported the practice of end-to-side anastomosis over end-to-end to preserve distal blood flow in lower extremity microvascular reconstruction. The "Godina's method" of treating complex lower extremity wounds with early radical debridement, skeletal fixation, and soft tissue coverage has stood the test of time in reducing complications such as osteomyelitis and nonunion. Along with systemic antibiotics, the use of

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antibiotic impregnated cement was introduced by orthopaedic surgeons in the 1970s and remains useful in lower extremity reconstruction.[9]

The Orthoplastic Approach

First coined by the senior author (L.S.L.) in the early 1990s, the collaborative orthoplastic approach between orthopaedic and plastic surgeons in limb salvage for the past several decades has resulted in a unique field of reconstructive surgery.[12] Specifically, he commented on using the reconstructive ladder as a means of employing different strategies of increasing complexity for soft tissue defects.[12] The lower rungs of the ladder include simpler reconstructive options such as the use of split-thickness skin grafts, and the higher rungs represent complex techniques such as free tissue transfer. In general, the lowest rung that is able to cover the defect adequately and replace the missing tissue components should be the reconstruction of choice. With time, orthoplastic surgery became known as "the principles and practices of both specialties applied to a clinical problem either by a single provider, or teams of providers working in concert for the benefit of the patient."[12–14]

Undoubtedly, orthopaedic and plastic surgeons have distinct strengths when it comes to lower extremity reconstruction. Plastic surgeons are equipped with a broad armamentarium of local and distant flap options for soft tissue coverage as well as vascularized bone grafts to reconstruct bony defects. For traumatic wounds, orthopaedic surgeons are critical in the initial wound assessment as well as diagnosing and stabilizing fractures by way of provisional and definitive fixation. Following resection of primary osseous or soft tissue sarcomas, skeletal and soft tissue reconstruction unites the interdisciplinary skillsets of plastic and orthopaedic surgeons.[1] In the ideal orthoplastic approach, both surgeon teams work in close unity during preoperative planning, intraoperative decision-making, and post-operative care/follow-up. Whether at the initial presentation following trauma, in cases of tumor resection that would require reconstruction, or when assessing nonhealing wounds in a diabetic patient with underlying peripheral vascular disease, the orthoplastic approach is useful.[1,15] Procedures should be planned with input from plastic surgeons to ensure adequate soft tissue coverage while also considering potential subsequent osseous interventions.

Orthoplastic Reconstructive Principles

With regards to patients with traumatic lower extremity injuries, multiple injury scoring systems have attempted to identify lower extremity trauma patients who would benefit from amputation versus salvage. Unfortunately, these all lack the sensitivity required to identify patients with nonsalvageable limbs in the acute setting and do not correlate with immediate or long-term functional outcomes.[16,17] This makes an orthoplastic approach to diagnosis even more critical and the subsequent treatment should be organized—our algorithmic approach has been previously describe (►**Fig. 1**).[18] The overarching principles that guide management of lower extremity wounds include restoring/optimizing distal blood flow, bony stabilization, and soft tissue reconstruction. These principles hold true whether reconstructing a traumatic wound, a defect following oncologic surgery, nonhealing diabetic wounds, or a wound with infected/exposed hardware.[1,19–21] For instance, following oncologic surgery, reconstructive goals include preserving function, maintaining a reasonable aesthetic outcome, and providing adequate lower soft tissue coverage to allow for adjuvant therapy (e.g., radiation).[1] Particularly when considering oncologic outcomes following resection of lower extremity tumors, avoiding adequate margins to close a defect by simpler means is no longer a concern when an orthoplastic team approach is used.[1] In cases of trauma, determining the severity of injury based on Gustilo–Anderson classification and the involvement of nerves, tendons, bone, and soft tissue is critical (►**Table 1**).[22–24] A lower grade Gustilo–Anderson fracture, IIIA, may just need fracture stabilization, debridement, and closure with primary/local soft tissue coverage. A higher-grade Gustilo–Anderson fracture, IIIC, will need emergent revascularization prior to further reconstructive procedures.

Vascular injury not only affects perfusion to the extremity, but it appears to serve as a surrogate marker for trauma severity and also hinders long-term function.[25,26] Whether in a trauma patient or in a diabetic patient with peripheral vascular disease, distal blood flow should be assessed prior to reconstructing any lower extremity wound, by way of physical exam, ankle–branchial indices, duplex ultrasonography, or computed tomography (CT) angiogram. In fact, peripheral vascular disease and major vascular compromise have been shown to be predictors of chronic osteomyelitis.[27] CT angiogram is useful in determining inflow, runoff, and any potential interruptions in blood flow. Duplex ultrasonography will help to ensure that venous outflow is not an issue. Any concern for vascular injury or preexisting pathology warrants a consultation with a vascular surgeon. This is particularly important in high-risk patients with diabetes, peripheral vascular disease, venous insufficiency, advanced age, or smoking history. If emergent revascularization is necessary, initial bony stabilization is achieved with external fixation, keeping in mind the exposure necessary for the vascular bypass. In cases of oncologic resection and reconstruction, tumor vessel involvement should be anticipated along with a plan to reestablish distal blood flow. Vascular bypass or stenting procedures may be necessary to augment flow to the distal extremity. In our experience, the posterior tibial artery is the most commonly selected recipient target (►**Fig. 2**), while the anterior tibial artery is preferred for free flap coverage of the dorsum of the foot, the lateral malleolus and lower leg, or if the patient is supine.[28] We prefer reconstruction with autologous conduit over prosthetic options, end-to-side anastomosis to prevent disruption of distal perfusion, and anastomosis to a vessel that shows no sign of injury/pathology when possible.[29,30] As first advocated by Serafin and Voci in 1983, anastomosis outside of the zone of injury is paramount to successful free tissue transfer in the lower extremity and can be performed either proximally or distally.[31,32] Furthermore, when the recipient vessel is not in continuity due to trauma or tumor

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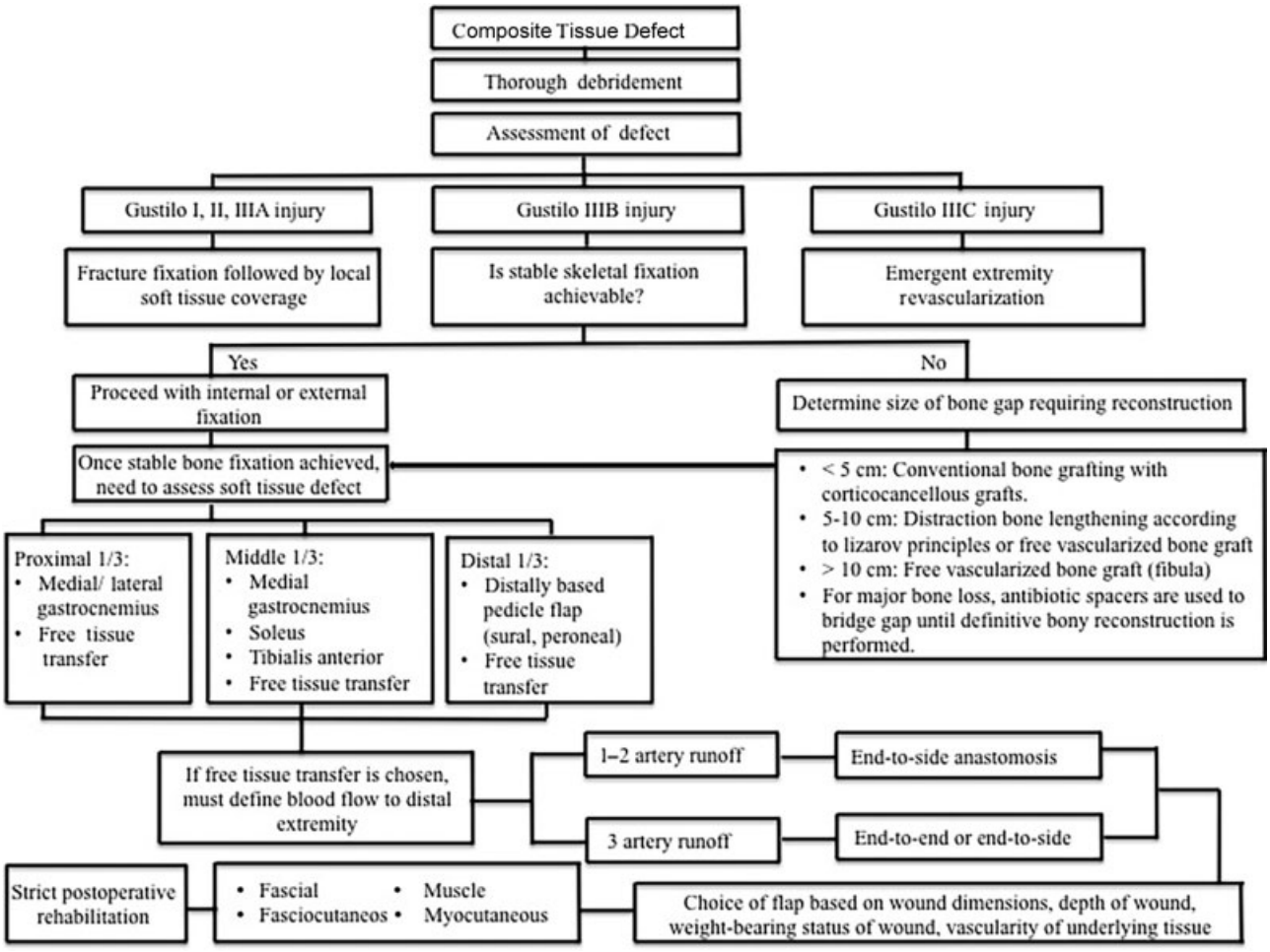

Fig. 1 Algorithm for orthoplastic management of composite defects of the lower extremity below the knee (from Sbitany H, Au AF. Stephen J. Kovach LSL. Orthoplastic approach to composite tissue loss. In: Pu LLQ, Levine JP, Wei F-C, eds. Reconstructive Surgery of the Lower Extremity. St. Louis, MO: Quality Medical Publishing Inc; 2013:1025–1045).[18]

extirpation, the anastomosis may be performed end-to-end. It is important to note that a vascular injury should raise suspicion for possible nerve injury. One should assess for nerve injury at the time of surgical exploration. Sharp nerve transections may be repaired primarily, but if the mechanism is a crush or blast injury, tag and delayed repair is preferred.[33]

Table 1 Gustilo–Anderson classification of open tibial fractures

Gustilo–Anderson classification of open fractures of the tibia	
I	Clean wound < 1 cm in diameter with simple fracture pattern with no soft tissue damage
II	Open fracture, laceration > 1 cm and < 10 cm without significant soft tissue damage
III	Open fracture with extensive soft tissue injury > 10 cm, loss or an open segmental fracture
IIIA	Adequate soft tissue coverage of the fracture despite high energy trauma or extensive laceration or skin flaps
IIIB	Inadequate soft tissue coverage with periosteal stripping
IIIC	Any open fracture that is associated with vascular injury that requires repair

In keeping with the aforementioned principles learned from Godina, thorough debridement of all nonviable tissue and implants is paramount to future successful reconstruction. This may require more than one procedure, with temporary "wet-to-wet" dressing changes, antibiotic bead pouches, or negative pressure wound therapy (vacuum-assisted closure [VAC]) until the wound bed is appropriate for coverage. The VAC should be changed every 24 to 48 hours to assess need for additional debridement, and it is no substitute for early well-vascularized tissue coverage (►**Fig. 3**).

The Arbetigemenschaft fur Osteosynthesfragen group (AO Foundation) for the study of internal fixation was formed in 1958 with a focus on patients with musculoskeletal injuries and related disorders.[34] The focus of AO is to provide care that will allow a patient to return to function and mobility. The management principles include fracture reduction and fixation to restore anatomical relationships, fracture fixation providing absolute or relative stability as the fracture patient and injury requires, preservation of blood supply to soft tissues and bone by gentle reduction techniques and careful handling,

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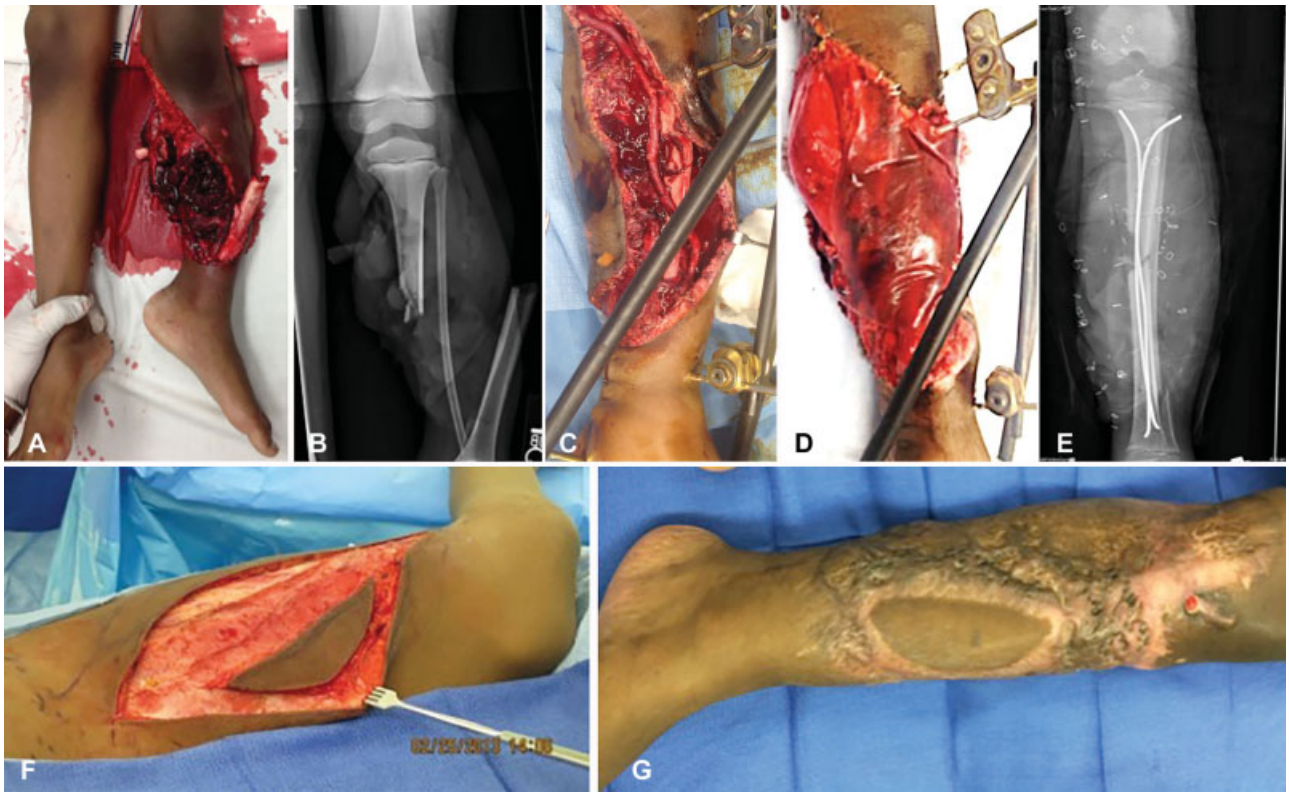

Fig. 2 (**A**) 8-year-old child presenting with a Gustilo IIIC injury (open tibial fracture and posterior tibial artery avulsion) following motor vehicle accident. (**B**) Radiograph demonstrating mid-shaft fracture of the tibia. (**C**) Fracture was stabilized with external fixation and a vascular bypass was performed from proximal to distal posterior tibial artery with reversed saphenous vein. (**D**) Provisional coverage was achieved for 24 hours with dermal substitute. (**E**) Conversion to internal fixation. (**F**) Free latissimus myocutaneous flap reconstruction as well as skin graft was performed on day 3 postinjury as a single procedure by an orthoplastic team to provide adequate soft tissue coverage of the vascular bypass. (**G**) Patient developed hypertrophic scarring of his skin graft but had a functional extremity at long-term follow-up.

Fig. 3 (**A**) 5-year-old child run over by a lawnmower. (**B**) Patient suffered extensive injuries of bilateral lower extremities with exposed bone, tendons, and nerves with large soft tissue deficit. (**c**) Chopart's amputation was performed on his left side and debridement of his right side (**D**) Initial coverage was provided with negative pressure wound therapy. (**E**) Free tissue transfer was performed using anterolateral thigh flap. Patient achieved full ambulatory status at 6 months following initial injury.

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and early mobilization and rehabilitation of the injured part and patient as a whole. Bony injuries without any missing segment can be stabilized with intramedullary rods or external fixation, with the aid of plating when necessary.

When a long-bone defect is present but less than 5 cm in length, a combination of antibiotic-impregnated spacer grafts and nonvascularized corticocancellous bone graft may be used for reconstruction. When used for appropriately sized defects, allograft success rate is 60 to 80%, but there remains the risk of nonunion, infection, and fracture.[18] For defects greater than 5 cm, the use of a vascularized bone graft is preferred and the free fibula is the most commonly used. This involves transfer of bone with its native blood supply to the defect and anastomosing the artery and vein. When used for these large defects, the osteocutaneous fibula flap can provide up to 18 to 20 cm of intercalary vascularized bone. Other options include the iliac crest, rib, radius, and scapula. When free vascularized bone is not favored/possible, the thin-wire fixation (the Ilizarov's method) in addition to distraction osteogenesis and bone transport has been used successfully for severe lower extremity defects >5 cm with good long-term outcomes.[35] However, this technique is often not performed, as the required distraction period may be significant. Although surrounding soft tissue lengthens along with the bone in the distraction technique, in a traumatic setting, additional soft tissue coverage procedures may be warranted. More functional results are also being achieved with angular correction of bony deformity and juxta-articular deformities. When a joint needs to be resected, reconstruction can be achieved with osteoarticular allografts, endoprosthetic implants, rotationplasty, and arthrodesis.

Once skeletal fixation has been achieved and devitalized tissue debrided, soft tissue deficit should be addressed in a timely manner. Although Godina demonstrated decreased nonunion, infection, and osteomyelitis in patients undergoing soft tissue coverage within 72 hours of injury, delay beyond that time frame may yield similar promising results.[9,11,36,37] This is likely in part related to other advances made in the management of these patients, such as better infection control with local and systemic antibiotics, as well as the use of negative pressure wound therapy for provisional coverage. Our preference on timing for soft tissue reconstruction is ideally within 5 to 7 days of injury.

Options for well-vascularized soft tissue coverage are dictated by the defect location and structures involved, and the reconstructive ladder continues to grow.[38] One way to categorize free flaps is to arrange them according to the tissue they contain, such as muscle, myocutaneous, fasciocutaneous, fascial, or bone. Cutaneous flaps such as the scapular, radial forearm, or anterolateral thigh flap provide pliability and good aesthetics. Muscle flaps such as the latissimus provide a large surface area that contours to irregular wound beds and are well perfused. Such a flap is a good choice for large three-dimensional cavitary defects or in the presence of osteomyelitis or exposed hardware. Muscle flaps are also useful in cases following oncologic resection when future radiotherapy is planned to avoid nonunion, fracture, or exposed hardware.[39,40] Fasciocutaneous flaps such as the anterolateral thigh flap can also be used over exposed hardware, as well as the plantar weight-bearing surface of the foot. These flaps provide a smooth, gliding surface that can be reelevated, and are also be used for defects around the metaphyseal regions of the ankle and knee with equal efficacy as muscle flaps.[33] The gastrocnemius and soleus muscles remain the workhorse pedicled flaps for the proximal and middle third of the lower extremity, respectively. Due to the relative paucity of local soft tissue, the distal third of the extremity more often warrants free flap coverage and the anterolateral thigh flap is our preferred perforator flap for coverage. It is important to note that some defects may require multiple ladder rungs used in tandem. Commonly used flap types for lower extremity will be covered elsewhere in this special issue.

Orthoplastic Approach Leads to Improved Outcomes

Recent study findings suggest that an orthoplastic approach improves patient outcomes compared with historical "piecemeal" approach.[41] Recent data supports the benefits of the management of lower extremity wounds at adult and pediatric trauma centers with early orthopaedic and plastic surgery input.[42,43] The interdisciplinary approach reduces the number of overall procedures necessary to achieve similar outcomes.[26] Measures such as pain, time to definitive skeletal stabilization/soft tissue coverage, function, length of hospital stay, postoperative complications, and need for revision procedures are improved with this approach.[41,43,44] In cases of pediatric lower extremity trauma with vascular compromise, the implementation of protocols that necessitate early triage by a microvascular surgeon improves response time and appropriate treatment.[42] Dedicated operating sessions with plastic and orthopaedic surgeons for patients with open fractures and complex soft tissue injuries also decreases timing to soft tissue coverage.[45] It is not surprising then that single-stage orthoplastic reconstruction has been shown to reduce infection rates following Gustilo–Anderson Grade III open fracture.[15,46] When considering cases of osteomyelitis, adequate débridement, skeletal reconstruction, and obliteration of dead space with a perforator flap results in a primary remission rate of 91.6% and a secondary remission rate of 98.3%.[27] When utilizing an orthoplastic approach for lower extremity reconstruction following oncologic surgery, limb salvage has success rates approaching 95%.[1]

Given the current evidence, future efforts to increase collaboration and develop new techniques/technologies in the management of these challenging patients will uncover additional advantages of the orthoplastic approach. One thing is certain, the orthoplastic approach has no clear disadvantages.

Penn L.E.G. (Lower Extremity Guide) Trauma Transfer

The best data on the topic of amputation versus limb salvage comes from the Lower Extremity Assessment Project (LEAP) study.[47] The findings of this study suggests that patients with

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Table 2 Penn L.E.G.(Lower Extremity Guidelines) trauma referral

Open fracture or exposed bone/joint with soft tissue loss not amenable to primary closure
Open fracture with bone loss
Open fracture with significant comorbidities
Absent pedal pulses, concern for dysvascular limb
Absent plantar sensation, concern for nerve injury
Significant foot/ankle soft tissue loss, including any plantar soft tissue loss
Fracture with associated compartment syndrome
Crush or blast mechanism injury involving multiple fascial compartments
Patients who will require special social, psychological, or rehabilitative intervention
Polytrauma with limb injury meeting above criteria following initial stabilization in a trauma center as necessary based on triaging physician's judgement

high-grade traumatic lower extremity wounds undergoing reconstruction have at least similar outcomes to those undergoing amputation.[47] Surprisingly, a review of participants of the study demonstrated that plastic surgeons were only directly involved in 14% of cases and somewhat involved in another 12%.[48] Proceeding with an amputation rather than salvage may have been related to providers being less familiar with complex reconstructive techniques, lack of access to collaborative resources, or based on common misconceptions such as nerve injury. Significant medical comorbidities or socioeconomic factors that could hinder the more prolonged clinical course of complex limb salvage may also have played a role in the decision making process. It may be assumed that if a comprehensive orthoplastic approach had been utilized throughout the study, more patients may have undergone attempted salvage with potentially higher success rates.

To address these potential treatment discrepancies and streamline care of patients at risk of amputation due to complex trauma, bone loss, soft tissue compromise or infection, the Penn Orthoplastic Limb Salvage Center was created. To our knowledge, this is the first center in the United States dedicated for patients at high-risk for amputation. Through this program, experts in microvascular surgery, complex fracture care, and various other limb salvage techniques work closely together to help patients avoid amputation. Dedicated rehabilitation therapists and social workers familiar with the needs of limb salvage patients play an integral role in ensuring continued access to care, especially considering the impact of socioeconomic status on successful limb salvage outcomes.[49]

Equally important to specialized multidisciplinary care, expediting early diagnosis and treatment of patients with traumatic lower extremity wounds through implementation of protocols leads to improved outcomes.[42] Although prior studies have urged immediate transfer and early combined surgery of patients with open tibial fractures, proposals on how this can be facilitated are lacking.[50] Similar to the American Burn Association (ABA) criteria for burn center referral, we believe that there should be a set of criteria to facilitate immediate transfer of patients with severe lower extremity injuries to a center with orthoplastic expertise.[51] For instance, it has been shown that a major factor delaying soft tissue coverage beyond 7 days includes transfer from another hospital.[52] We have devised a list of guidelines that may help centers in this oftentimes challenging decision-making process based on the best available evidence and expert opinion (►**Table 2**).[48,53–58] In the least, this should offer comfort to providers in community locations to reach out to tertiary centers when considering transfer. We respect the principle of "life over limb" in that transfer should occur once all life-threatening injuries are stabilized. It is important to note that this is a guide and when in doubt, consultation with a tertiary dedicated trauma center is encouraged.

Future Directions

The use of negative pressure wound therapy, dermal substitutes, and the increasing adoption of perforator flaps for coverage with reduced donor site morbidity are just a few of the recent advances in lower extremity reconstruction. Despite significant progress in the field of limb salvage; however, the best evidence to date demonstrates clinical outcomes that fall short of our high expectations for functional recovery and patient quality of life. Promoting the value of a multidisciplinary approach, specifically orthoplastic surgery, has the potential to result in a higher rate of successful limb salvage in patients at risk for amputation.

The success of prosthetics and vascularized composite allotransplantation will have a significant effect on the long-term future of lower extremity reconstruction. Outcomes following salvage are similar to those after amputation and decision-making continues to be guided by patient preference and provider expertise. A future goal should be to better predict those who would perform better with reconstruction or amputation/prosthesis. Until amputation and prosthesis prove to be better than limb salvage from a financial, safety and outcomes point of view, patients may continue to prefer reconstruction. For this reason, orthoplastic teams must continue to be trained in complex/microsurgical reconstruction and work together to deliver the best care possible to these patients.

Conclusion

The orthoplastic approach to lower extremity reconstruction is a collaborative model of orthopaedic and plastic surgeons working together to expedite and optimize care of patients in need of lower extremity reconstruction. The implementation of protocols, systems, and centers that foster this approach leads to improved outcomes for these patients. When faced with challenging cases of chronic osteomyelitis, nonhealing wounds in diabetic patients, large tumors, or high grade traumatic injuries, we encourage centers to embrace the orthoplastic approach when considering limb salvage, as the decision to amputate is irreversible.

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Conflict of Interest
None declared.

References

1 Suh HS, Lee JS, Hong JP. Consideration in lower extremity reconstruction following oncologic surgery: Patient selection, surgical techniques, and outcomes. J Surg Oncol 2016;113(08):955–961
2 Lerman OZ, Kovach SJ, Levin LS. The respective roles of plastic and orthopedic surgery in limb salvage. Plast Reconstr Surg 2011;127 (Suppl 1):215S–227S
3 Bell B. A brief review and estimate of the professional writings of Benjamin Bell, F.R.C.S.E., F.R.S.E., Author of "A System of Surgery," and other works. Edinburgh Med J 1868;14(05):408–433
4 Lister J. On a new method of treating compound fracture. 1867;89 (2274): 387–389
5 Friedlaender GE, Friedlaender LK. Art in science: the Gross Clinic by Thomas Eakins. Clin Orthop Relat Res 2014;472(12): 3632–3636
6 Huntington TW. The classic: Case of bone transference. Use of a segment of fibula to supply a defect in the tibia. 1905. Clin Orthop Relat Res 2012;470(10):2651–2653
7 Stark WJ. The use of pedicled muscle flaps in the surgical treatment of chronic osteomyelitis resulting from compound fractures. J Bone Joint Surg Am 1946;28:343–350
8 Daniel RK, Taylor GI. Distant transfer of an island flap by microvascular anastomoses. A clinical technique. Plast Reconstr Surg 1973;52(02):111–117
9 Colen DL, Colen LB, Levin LS, Kovach SJ. Godina's principles in the twenty-first century and the evolution of lower extremity trauma reconstruction. J Reconstr Microsurg 2018;34(08): 563–571
10 Hong JPJ, Colen LB. How has Dr. Marko Godina influenced us? Plast Reconstr Surg 2017;140(03):641–642
11 Godina M. Early microsurgical reconstruction of complex trauma of the extremities. Plast Reconstr Surg 1986;78(03):285–292
12 Levin LS. The reconstructive ladder. An orthoplastic approach. Orthop Clin North Am 1993;24(03):393–409
13 Zenn MR, Levin LS. Microvascular reconstruction of the lower extremity. Semin Surg Oncol 2000;19(03):272–281
14 Levin LS, Erdmann D. Primary and secondary microvascular reconstruction of the upper extremity. Hand Clin 2001;17(03): 447–455, ix
15 Mathews JA, Ward J, Chapman TW, Khan UM, Kelly MB. Single-stage orthoplastic reconstruction of Gustilo-Anderson Grade III open tibial fractures greatly reduces infection rates. Injury 2015; 46(11):2263–2266
16 Ly TV, Travison TG, Castillo RC, Bosse MJ, MacKenzie EJ; LEAP Study Group. Ability of lower-extremity injury severity scores to predict functional outcome after limb salvage. J Bone Joint Surg Am 2008;90(08):1738–1743
17 Bosse MJ, MacKenzie EJ, Kellam JF, et al. A prospective evaluation of the clinical utility of the lower-extremity injury-severity scores. J Bone Joint Surg Am 2001;83(01):3–14
18 Sbitany H, Au AF, Kovach SJ, Levin LS. Orthoplastic approach to composite tissue loss. In: Pu LLQ, Levine JP, Wei FC, eds. Reconstructive Surgery of the Lower Extremity. St. Louis, MO: Quality Medical Publishing Inc; 2013:1025–1045
19 Suh YC, Kushida-Contreras BH, Suh HP, et al. Is reconstruction preserving the first ray or first two rays better than full transmetatarsal amputation in diabetic foot? Plast Reconstr Surg 2019; 143(01):294–305
20 Suh YC, Suh HP, Lee JS, Chang JS, Hong JPJ. Reconstruction using a perforator free flap after malignant melanoma resection of the ankle and foot. J Surg Oncol 2017;116(07):862–869
21 Nguyen T, Rodriguez-Collazo ER. Healing heel ulcers in high-risk patients: Distally based peroneus brevis muscle flap case series. J Foot Ankle Surg 2019;58(02):341–346
22 Gustilo RB, Anderson JT. Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses. J Bone Joint Surg Am 1976;58(04):453–458
23 Gustilo RB, Mendoza RM, Williams DN. Problems in the management of type III (severe) open fractures: a new classification of type III open fractures. J Trauma 1984;24(08):742–746
24 Gustilo RB, Merkow RL, Templeman D. The management of open fractures. J Bone Joint Surg Am 1990;72(02):299–304
25 Stranix JT, Lee ZH, Jacoby A, et al. Not all Gustilo type IIIB fractures are created equal: arterial injury impacts limb salvage outcomes. Plast Reconstr Surg 2017;140(05):1033–1041
26 Chummun S, Wright TC, Chapman TWL, Khan U. Outcome of the management of open ankle fractures in an ortho-plastic specialist centre. Injury 2015;46(06):1112–1115
27 Hong JPJ, Goh TLH, Choi DH, Kim JJ, Suh HS. The efficacy of perforator flaps in the treatment of chronic osteomyelitis. Plast Reconstr Surg 2017;140(01):179–188
28 Tintle SM, Levin LS. The reconstructive microsurgery ladder in orthopaedics. Injury 2013;44(03):376–385
29 KhourI RK, Shaw WW. Reconstruction of the lower extremity with microvascular free flaps. J Trauma Inj Infect Crit Care 2006; 29:1086–1094
30 Samaha FJ, Oliva A, Buncke GM, Buncke HJ, Siko PP. A clinical study of end-to-end versus end-to-side techniques for microvascular anastomosis. Plast Reconstr Surg 1997;99(04): 1109–1111
31 Serafin D, Voci VE. Reconstruction of the lower extremity. Microsurgical composite tissue transplantation. Clin Plast Surg 1983;10 (01):55–72
32 Stranix JT, Borab ZM, Rifkin WJ, et al. Proximal versus distal recipient vessels in lower extremity reconstruction: a retrospective series and systematic review. J Reconstr Microsurg 2018;34 (05):334–340
33 Fang F, Chih-Hung L. Lower extremity reconstruction. In: Wei FC, Mardini S, eds. Flaps and Reconstructive Surgery. 2nd ed. London: Elsevier; 2016:255–274
34 Ruedi TP, Buckley RE, Moran CG. AO Principles of Fracture Management. 2nd ed. New York: Thieme; 2007
35 Lowenberg DW, Buntic RF, Buncke GM, Parrett BM; D.W. L. Long-term results and costs of muscle flap coverage with Ilizarov bone transport in lower limb salvage. J Orthop Trauma 2013;27(10): 576–581
36 Steiert AE, Gohritz A, Schreiber TC, Krettek C, Vogt PM; A.E. S. Delayed flap coverage of open extremity fractures after previous vacuum-assisted closure (VAC) therapy-worse or worth? J Plast Reconstr Aesthet Surg 2009;62(05):675–683
37 Karanas YL, Nigriny J, Chang J. The timing of microsurgical reconstruction in lower extremity trauma. Microsurgery 2008; 28(08):632–634
38 Janis JE, Kwon RK, Attinger CE. The new reconstructive ladder: modifications to the traditional model. Plast Reconstr Surg 2011; 127(Suppl 1):205S–212S
39 Mastorakos DP, Disa JJ, Athanasian E, Boland P, Healey JH, Cordeiro PG. Soft-tissue flap coverage maximizes limb salvage after allograft bone extremity reconstruction. Plast Reconstr Surg 2002; 109(05):1567–1573
40 Gebhardt MC, Flugstad DI, Springfield DS, Mankin HJ. The use of bone allografts for limb salvage in high-grade extremity osteosarcoma. Clin Orthop Relat Res 1991:181–196
41 Boriani F, Ul Haq A, Baldini T, et al. Orthoplastic surgical collaboration is required to optimise the treatment of severe limb injuries: A multi-centre, prospective cohort study. J Plast Reconstr Aesthet Surg 2017;70(06):715–722
42 Gans I, Baldwin KD, Levin LS, et al. A lower extremity musculoskeletal and vascular trauma protocol in a children's hospital may improve treatment response times and appropriate microvascular coverage. J Orthop Trauma 2015;29(05):239–244

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43 Stammers J, Williams D, Hunter J, Vesely M, Nielsen D. The impact of trauma centre designation on open tibial fracture management. Ann R Coll Surg Engl 2013;95(03):184–187

44 Sommar P, Granberg Y, Halle M, Skogh ACD, Lundgren KT, Jansson KÅ. Effects of a formalized collaboration between plastic and orthopedic surgeons in severe extremity trauma patients; a retrospective study. J Trauma Manag Outcomes 2015;9:3

45 Fernandez MA, Wallis K, Venus M, Skillman J, Young J, Costa ML. The impact of a dedicated orthoplastic operating list on time to soft tissue coverage of open lower limb fractures. Ann R Coll Surg Engl 2015;97(06):456–459

46 Jenkinson RJ, Kiss A, Johnson S, Stephen DJG, Kreder HJ. Delayed wound closure increases deep-infection rate associated with lower-grade open fractures: a propensity-matched cohort study. J Bone Joint Surg Am 2014;96(05):380–386

47 Bosse MJ, MacKenzie EJ, Kellam JF, et al. An analysis of outcomes of reconstruction or amputation after leg-threatening injuries. N Engl J Med 2002;347(24):1924–1931

48 MacKenzie EJ, Bosse MJ, Kellam JF, et al; LEAP Study Group. Factors influencing the decision to amputate or reconstruct after high-energy lower extremity trauma. J Trauma 2002;52(04):641–649

49 MacKenzie EJ, Bosse MJ, Kellam JF, et al. Early predictors of long-term work disability after major limb trauma. J Trauma 2006;61 (03):688–694

50 Trickett RW, Rahman S, Page P, Pallister I. From guidelines to standards of care for open tibial fractures. Ann R Coll Surg Engl 2015;97(06):469–475

51 Carter JE, Neff LP, Holmes JH IV. Adherence to burn center referral criteria: are patients appropriately being referred? J Burn Care Res 2010;31(01):26–30

52 Rymer B, Dimovska EOF, Chou DTS, Choa R, Davis B, Huq S. A representative assessment of the management of open fractures of the lower limb within UK orthoplastic centres: A two-centre audit of compliance with national standards. Injury 2017;48(10): 2266–2269

53 Perkins ZB, Yet B, Glasgow S, et al. Meta-analysis of prognostic factors for amputation following surgical repair of lower extremity vascular trauma. Br J Surg 2015;102(05):436–450

54 Helgeson MD, Potter BK, Burns TC, Hayda RA, Gajewski DA. Risk factors for and results of late or delayed amputation following combat-related extremity injuries. Orthopedics 2010;33(09):669

55 Dickens JF, Kilcoyne KG, Kluk MW, Gordon WT, Shawen SB, Potter BK. Risk factors for infection and amputation following open, combat-related calcaneal fractures. J Bone Joint Surg Am 2013;95 (05):e24

56 Topal AE, Eren MN, Celik Y. Lower extremity arterial injuries over a six-year period: outcomes, risk factors, and management. Vasc Health Risk Manag 2010;6:1103–1110

57 McNutt R, Seabrook GR, Schmitt DD, Aprahamian C, Bandyk DF, Towne JB. Blunt tibial artery trauma: predicting the irretrievable extremity. J Trauma 1989;29(12):1624–1627

58 Kurup HV. A score for predicting salvage and outcome in Gustilo type-IIIA and type-IIIB open tibial fractures. J Bone Joint Surg Br 2007;89(04):562–562, author reply 562–563

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