Traumatic and Trauma-Related Amputations: Part I: General Principles and Lower-Extremity Amputations

LT Scott M. Tintle, CDR John J. Keeling, LTC Scott B. Shawen, LCDR Jonathan A. Forsberg and MAJ Benjamin K. Potter


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Deliberate attention to the management of soft tissue is imperative when performing an amputation. Identification and proper management of the nerves accompanied by the performance of a stable myodesis and ensuring robust soft-tissue coverage are measures that will improve patient outcomes.

Limb length should be preserved when practicable; however, length preservation at the expense of creating a nonhealing or painful residual limb with poor soft-tissue coverage is contraindicated.

While a large proportion of individuals with a trauma-related amputation remain severely disabled, a chronically painful residual limb is not inevitable and late revision amputations to improve soft-tissue coverage, stabilize the soft tissues (revision myodesis), or remove symptomatic neuromas can dramatically improve patient outcomes.

Psychosocial issues may dramatically affect the outcomes after trauma-related amputations. A multidisciplinary team should be consulted or created to address the multiple complex physical, mental, and psychosocial issues facing patients with a recent amputation.

In the United States alone, approximately 185,000 amputations are performed annually\(^1,2\), with about 16% of these being related to trauma. Despite this relatively low proportion of amputations done following trauma, individuals with a traumatic amputation account for nearly 45% of the estimated 1.6 million living people with an amputation\(^1\). This striking disparity highlights the most important difference between trauma-related amputations and those performed on more elderly or infirm individuals for other indications. Trauma-related amputations are usually performed on young and previously healthy patients with substantial predicted longevity as well as a high potential for rehabilitation to regain previous levels of activity\(^1\).

Historically, it was believed that individuals with a trauma-related amputation rapidly adapted to the loss of the limb and proceeded to lead functional and productive lives. Unfortunately, this proposition has not been substantiated by the literature, and it is now recognized that the postoperative course following a trauma-related amputation is fraught with complications and difficulties\(^4\). In a review highlighting the difficulties facing these individuals, Pierce et al.\(^3\) indicated that nearly 51% of their sixty-one patients developed an anatomic complication related to their amputation. This difficult postoperative course has also been recognized and discussed by the Lower Extremity Assessment Project (LEAP) study group. The authors of the LEAP study reported a rehospitalization rate of 29.8% and a 14.5% rate of revision of the residual limb in their series of 149 patients treated with trauma-related amputation\(^4\). Nonetheless, 6.5% of the 124 patients followed for twenty-four months still did not have fully healed soft tissues\(^4\). Most importantly, a large percentage of these patients

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become and remain severely disabled following a trauma-related amputation. Considering the potential for a young, previously healthy person returning to a high level of function after an amputation, it is imperative to provide a durable, painless residual limb capable of prolonged prosthetic wear. Despite the apparent simplicity of the procedure, the trauma-related amputation or revision of a traumatic amputation and the closure itself should not be considered a nuisance, treatment failure, or surgical opportunity for an unsupervised novice; rather, it is a challenge for even the experienced surgeon.

The two essential parts of a successful amputation include the removal of the damaged or dysfunctional portion of the limb followed by the reconstruction of the residual limb. The first goal is easily accomplished in all but the rarest of circumstances, whereas reconstruction of a durable residual limb is more challenging. Adherence to proper techniques (Table I) and the avoidance of well-documented technical errors (Table II) can dramatically affect the outcome and final function of the residual limb.

**Limb Salvage Versus Amputation**

**The Lower Extremity Assessment Project (LEAP) Study**

The findings of the LEAP study group have been reported over the past decade and have become important considerations when one is evaluating and counseling patients with severe lower-extremity trauma. The LEAP study was a prospective, multicenter, observational study of patients with severe lower-extremity trauma in the United States civilian population. The functional outcomes for 601 patients who had undergone either limb reconstruction or amputation were assessed. The authors recognized an important study selection bias in which study subjects were not randomly selected for amputation or limb salvage. The more severely injured patients were treated with amputation. Despite the fact that the LEAP study is the largest and best scientifically planned study of its type to date, it remains controversial and is cited by both advocates for limb salvage and those for amputation as support for their professional preferences, practices, and opinions. Regardless of where one’s opinions fall in the limb salvage versus amputation debate, careful scrutiny of the study reveals issues such as the lack of randomization, the limitations of the Sickness Impact Profile scores, and the limitations with regard to the conclusions reached.

### Table I: Checklist for Successful Performance of Trauma-Related Amputations

<table>
<thead>
<tr>
<th>Technical Error</th>
<th>Resulting Complication(s)</th>
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<tbody>
<tr>
<td>Perform an aggressive initial (and subsequent) debridement and irrigation; do not attempt to definitively close the wound at the index procedure</td>
<td>Length salvage may be inappropriately aggressive with little concern for soft-tissue coverage, leading to a poorly padded residual limb; conversely, length selection may be overly conservative, leading to an unnecessarily shortened residual limb</td>
</tr>
<tr>
<td>Preserve reconstructive options via appropriate length selection and salvage of all viable tissue at the initial debridement procedure</td>
<td>Symptomatic neuromas, which can negatively affect prosthetic wear or require revision surgery</td>
</tr>
<tr>
<td>Salvage functional joint levels; manage proximal fractures via standard techniques</td>
<td>Inappropriate handling of the periosteum or failure to smooth bone ends may lead to sharp, symptomatic spurs or edges</td>
</tr>
<tr>
<td>Perform a traction neurectomy for all named nerves and all grossly visible cutaneous nerves well proximal to the end of the residual limb</td>
<td>Decreased residual limb control, retraction of distal padding, or overt subluxation or snapping of distal muscle groups</td>
</tr>
<tr>
<td>Identify, isolate, and securely ligate all named vessels</td>
<td>Delayed healing, pain, and soft-tissue breakdown</td>
</tr>
<tr>
<td>Bevel and smooth all sharp bone ends of the residual limb; respect the periosteum</td>
<td>Decreased residual limb control and proximal joint contractures</td>
</tr>
<tr>
<td>Perform a stable myodesis under physiologic muscle tension and augment with a secondary myoplasty</td>
<td>Dog ears, or soft-tissue redundancy, producing ulceration or pain</td>
</tr>
<tr>
<td>Ensure robust and viable distal padding</td>
<td>Failure to adequately recognize and treat frequent complications</td>
</tr>
<tr>
<td>Maintain close follow-up in the early postoperative period and then pursue a consistent subsequent follow-up plan to identify operative complications and problems early and prevent nonoperative issues from escalating into operative ones</td>
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### Table II: Documented Technical Errors in the Operative Care of Trauma-Related Amputations and Subsequent Untoward Results

<table>
<thead>
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<tr>
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<td>Failure to perform traction neurectomies</td>
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<tr>
<td>Inappropriate management of bone</td>
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</tr>
<tr>
<td>Failure to adequately stabilize distal musculature</td>
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</tr>
<tr>
<td>Failure to achieve a robust distal soft-tissue envelope</td>
<td>Delayed healing, pain, and soft-tissue breakdown</td>
</tr>
<tr>
<td>Failure to balance remaining muscular forces on the residual limb</td>
<td>Decreased residual limb control and proximal joint contractures</td>
</tr>
<tr>
<td>Inadequate attention to balanced incision closure</td>
<td>Dog ears, or soft-tissue redundancy, producing ulceration or pain</td>
</tr>
<tr>
<td>Inadequate short and intermediate-term follow-up</td>
<td>Failure to adequately recognize and treat frequent complications</td>
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concerning through-the-knee amputations that should be considered when interpreting the results of this nonetheless landmark study.

In the LEAP series, the outcomes in both the limb salvage and the amputation group were poor. One-half of the patients in both cohorts had substantial disability. Despite equivalent early costs in the two groups, the lifetime cost for the amputation group was estimated to be about three times higher secondary to prosthesis-related expenses. The LEAP study also showed that multiple scoring systems did not reliably predict the fate of the injured extremities or the functional outcomes of the patients. The evaluated scoring systems were the Mangled Extremity Severity Score; the Limb Salvage Index; the Predictive Salvage Index; the Nerve Injury, Ischemia, Soft-Tissue Injury, Skeletal Injury, Shock, and Age of Patient Score; and the Hannover Fracture Scale-98. The study group also found that an insensitive foot on presentation should not be a critical indication for amputation, as there was a return of plantar sensation by two years in the majority of cases. Finally, the study demonstrated that predictors of lower scores on the Sickness Impact Profile included a low educational level, non-white race, poverty, a lack of private health insurance, a poor social-support network, low self-efficacy, smoking, and involvement in disability-compensation litigation.

**Indications for Lower-Extremity Amputation**

The majority of the literature addressing lower-extremity trauma and amputation has dealt with open tibial fractures; thus, the majority of the literature addressing the issue of limb salvage versus amputation deals with that particular injury. Suggested absolute indications for lower-extremity amputation are blunt or contaminated traumatic amputation, a mangled extremity in a critically injured patient in shock, or a crushed extremity with arterial injury and a warm ischemia time of greater than six hours. Other, relative indications for amputation include severe bone or soft-tissue loss; an anatomic transection of the tibial nerve; an open tibial fracture with serious associated polytrauma or a severe ipsilateral foot injury; and/or a prolonged predicted course to obtain soft-tissue coverage and tibial reconstruction. In addition to these relative indications, we have found that having at least two experienced surgeons provide a frank intraoperative assessment to be a relatively consistent way to decide whether a limb has the potential to be saved.

**Operative Techniques**

**Early Surgical Goals**

Initial goals in the treatment of a severe lower-extremity injury include control of life-threatening hemorrhage and patient stabilization followed by thorough debridement of all contaminated wounds. All devitalized muscle, skin, and bone without articular cartilage that is devoid of soft-tissue attachments must be excised sharply. Conversely, viable muscle and fasciocutaneous tissue should be saved for possible use in the definitive soft-tissue reconstruction. While conclusions regarding the optimal methods of irrigation of contaminated wounds have varied in the literature, we currently recommend irrigation with 9 L of normal saline solution utilizing either low-pressure gravity-flow irrigation or low-pressure pulsatile lavage (psi < 10). This recommendation is based on mounting evidence that higher-pressure pulsatile lavage causes host-tissue damage and edema and produces a significantly greater bacterial rebound (p = 0.048) than irrigation with a simple bulb syringe.

While it is common that the bacterial counts within traumatic wounds slowly increase following irrigation and debridement procedures, Owens et al. found that, with pulsatile lavage, the bacterial count following irrigation and debridement increased to 94% of the count before the irrigation and debridement in an animal model, whereas the bacterial count rebounded to only 48% of the pre-irrigation and debridement count when a bulb syringe was utilized. This presumably occurs as a result of the damage caused by pulsatile lavage as well as the pressure from the device driving bacteria deeper into local tissues.

In most instances, at least one additional irrigation and debridement procedure will and should take place. Therefore, we recommend performing a length-preserving amputation that retains any irregular but grossly viable muscle and skin rather than creating formal flaps for closure at the initial debridement. This length-preserving technique and these so-called flaps of opportunity allow maximal length preservation and maintain potentially useful soft tissue for bone coverage and padding (Figs. 1-A and 1-B). The so-called guillotine amputation is an antiquated technique that only serves to compromise length and level salvage and has few modern indications, with the possible exception of an initial guillotine amputation followed by a planned, staged closure at an entirely different, more proximal level (e.g., a “guillotine” ankle disarticulation in the face of a degloved or nonviable heel pad prior to a planned revision to a transtibial level) (Fig. 2).

**Definitive Wound Management**

Often, multiple irrigation and debridement procedures are necessary, and the use of negative-pressure wound therapy may prove to be a useful adjuvant until the time of definitive amputation revision. Similar to the highly touted skin-traction techniques that were popularized during previous military conflicts, negative-pressure wound therapy with the addition of vessel loops utilized in a so-called Jacob’s ladder or shoelace manner may contribute to the salvage of post-amputation length. Repeat irrigation and debridement procedures should be performed every forty-eight to seventy-two hours until the wound is thought to be clean and without nonviable tissue. Despite the technological advances in the treatment of severe lower-extremity trauma, the timing of wound closure remains the subjective decision of the surgeon and depends mostly on the appearance of the bone and soft tissues and, to a lesser degree, on laboratory values and the patient’s overall condition.

In addition to negative-pressure wound therapy, antibiotic-impregnated polymethylmethacrylate beads have been frequently used in the provisional management of trauma-related extremity amputations. The study of the use of antibiotic beads

**Skeletal Injury, Shock, and Age of Patient Score; and the Hannover Fracture Scale-98.**

1. **In the LEAP series, the outcomes in both the limb salvage and the amputation group were poor. One-half of the patients in both cohorts had substantial disability.**

2. **Concerning through-the-knee amputations that should be considered when interpreting the results of this nonetheless landmark study.**

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16. **In addition to negative-pressure wound therapy, antibiotic-impregnated polymethylmethacrylate beads have been frequently used in the provisional management of trauma-related extremity amputations. The study of the use of antibiotic beads
Intraoperative photograph demonstrating atypical flaps utilized to salvage residual limb length in a proximal transfemoral amputation prior to closure. The proximal part of the quadriceps and the anterior thigh skin have been lost as a result of trauma, leading to exposed bone and inadequate anterior soft-tissue coverage. This defect has been covered with a more proximal myoplasty of the viable remaining hamstring muscles (a) following adductor myodesis to permit salvage of residual limb length, and soft-tissue closure is facilitated by retention of atypical viable posteromedial (b) and lateral (c) fasciocutaneous flaps. Fig. 1-B The same residual limb following definitive wound closure.
in humans has proven difficult because of host and wound variability; however, animal data have demonstrated efficacy of local antibiotic beads within open wounds to prevent infection\(^\text{25}\). While bead pouches and the temporary closure of residual limbs over antibiotic beads have been utilized, we frequently use antibiotic beads in conjunction with negative-pressure wound therapy. However, the appropriate antibiotic concentrations remain unknown, and the efficacy of this regimen is unproven.

**Soft-Tissue Management**

**Muscle**

The condition of the soft-tissue envelope is perhaps the most important variable in determining the outcome of treatment of the limb. Surgeons usually utilize remaining viable muscle and fasciocutaneous tissues for soft-tissue coverage in an attempt to achieve a durable, well-padded limb. Muscle coverage over the residual bone provides padding as well as assists in control of the distal part of the extremity and overall limb alignment\(^\text{26,27}\).

Myodesis, myoplasty, and myofascial techniques are all utilized in amputation surgery to stabilize the residual muscle and maintain the distal bone end in a padded and covered position. Myodesis is achieved when a residual muscle and its fascia are sutured directly to bone through drill holes or are firmly attached to the periosteum (Figs. 3-A and 3-B). Myodesis provides the most structurally stable result. Myoplasty is performed by suturing a residual muscle agonist to its antagonist over the end of the bone to create physiologic tension. A myofascial closure, which involves suturing a residual muscle and its apposing fascia together, creates the least stable of the constructs.

Myodesis is the recommended technique when a trauma-related amputation is performed\(^\text{28,29}\). This technique restores
Intraoperative photographs demonstrating a myodesis to the anterior-distal aspect of the tibia before (Fig. 3-A) and after (Fig. 3-B) tying of the deep myodesis stitch with utilization of two parallel drill holes in the anterior aspect of the tibia and a number-5 nonabsorbable suture that has been buried laterally in a horizontal mattress fashion. Additional number-1 or number-0 sutures are then placed in a simple or figure-of-eight fashion approximately 4 to 5 cm proximal to the end of the bone where the distal myofascial flap terminates to reinforce the myodesis by anchoring it to the anterior tibial periosteum.
the physiologic muscle tension, secures the deep soft-tissue padding, prevents instability of the muscle unit, and allows for functional muscle use during walking\textsuperscript{30}. Myofascial and myoplasty closures (without myodesis) are frequently used both in patients with dysvascular/diabetic disorders and those with traumatic injury\textsuperscript{5,31,32}. Despite their frequency of use, these techniques should serve only as supplementary methods of muscle stabilization after performance of a myodesis in a patient undergoing a trauma-related amputation. Furthermore, there is no good clinical evidence contraindicating myodesis even in patients with a diabetic/dysvascular disorder, and perhaps more widespread utilization of this technique in those populations may be worthwhile to obtain the benefits discussed above.

**Nerve**

Neuroma formation is the seemingly inevitable biologic consequence of nerve transection when regenerating axons are incapable of reentering the distal nerve stump\textsuperscript{33}. The complete removal of the distal portion of a nerve in amputation surgery virtually ensures neuroma formation. An important consideration in amputation surgery is thus to try to prevent these neuromas from becoming symptomatic with prosthetic wear. Ebrahimzadeh et al. reported symptomatic neuromas in 13\% of ninety-six patients with a transtibial amputation and 32\% of thirty-one with a transfemoral amputation\textsuperscript{34,35}. These symptomatic neuromas are a common indication for revision surgery\textsuperscript{36-40}. Unfortunately, no technique has proven superior for the prevention of symptomatic neuroma formation\textsuperscript{38}. The most commonly performed of these procedures is the traction neurectomy, in which the nerve is pulled distally and then cut, placing the neuroma away from the definitive closure and the ligated vessels. When an amputation is performed, all important nerves should be identified and isolated (Fig. 4). Following this, a traction neurectomy should be performed well proximal to the weight-bearing portions of the terminal residual limb.

**Vessels**

All major arteries and veins should be individually identified and ligated with nonabsorbable suture (e.g., silk). The arteries with a neuroma and thus limit prosthetic wear. Frequently encountered locations for symptomatic neuromas in the lower extremity include the common peroneal nerve and the sural nerve. As a result of its subcutaneous location directly overlying the fibular head, the common peroneal nerve frequently becomes symptomatic following a transtibial amputation. A substantial amount of pressure from a prosthetic socket can develop over this osseous prominence and underlying neuroma. The sural nerve is often ignored when a transtibial amputation is performed.

Numerous techniques have been advocated to prevent or reduce formation of symptomatic neuromas; these include traction neurectomy, epineural and silicone capping, preemptive regional anesthetic blockade, and implantation of the cut nerve end into muscle or bone\textsuperscript{36-40}. Unfortunately, no technique has been universally accepted for the prevention of symptomatic neuroma formation\textsuperscript{38}. The most commonly performed of these procedures is the traction neurectomy, in which the nerve is pulled distally and then cut, placing the neuroma away from the definitive closure and the ligated vessels. When an amputation is performed, all important nerves should be identified and isolated (Fig. 4). Following this, a traction neurectomy should be performed well proximal to the weight-bearing portions of the terminal residual limb.

Fig. 4

Intraoperative photograph demonstrating a sciatic nerve that had been included in the amputation myoplasty. The resulting neuroma was symptomatic and precluded prosthetic wear and walking and required excision to a more proximal level, as shown in this photograph.
and veins should be ligated separately. We commonly utilize number-2-0 silk suture below the knee, while number-0 silk is used to ligate the popliteal or femoral artery, which is then double ligated with an additional number-2-0 suture ligature.

**Level of Amputation and Length Preservation**

The selection of the appropriate amputation level is critical to the final outcome. The energy required for walking increases as the amputation level moves proximally. The gait of an individual with an amputation is less efficient than normal gait, as demonstrated by increased rates of oxygen consumption and decreased customary walking speeds. The gait of an individual with an amputation depends on the proximal joints and muscles remaining to compensate for the lost joint and muscle function distal to the level of amputation. It is not therefore surprising that the oxygen cost is increased at each progressive amputation level from the transtibial to the trans-tibial level.

The increased rate of oxygen consumption by an individual with a transtibial amputation is similar to that of a patient who has undergone an ankle fusion. This factor highlights the fact that the loss of ankle joint mobility is the major biomechanical component responsible for the increased energy consumption following a transtibial amputation.

The gait of a patient with a transfemoral amputation is hindered not only by the loss of the ankle and the knee, but also by the weakened hip and thigh musculature. In addition, the lack of a direct connection between the human thigh and a prosthetic knee, as well as persistent limitations in prosthetic foot design, leads to a gait in which knee flexion serves only to allow foot clearance and does not contribute to load absorption. While an individual with a transtibial amputation also has abnormal load absorption during gait, as a result of decreased maximum knee flexion as compared with that during normal gait, even when a state-of-the-art prosthesis with microprocessors is used after a transfemoral amputation there is increasingly abnormal load acceptance during gait as a result of the minimal knee flexion at foot contact that is needed to ensure that the prosthetic knee does not collapse. These abnormalities combined with a decreased range of motion and strength of the ipsilateral hip and thigh lead to increased pelvic and trunk motion as well as compensatory mechanisms in the sound limb, involving all phases of gait, that lead to increased energy requirements for walking.

Because of these energy considerations, better outcomes are usually associated with joint-level preservation and a longer residual limb as long as length preservation does not negatively impact the quality of the soft-tissue coverage.

In a posttraumatic scenario, the level of the most severe soft-tissue injury will usually dictate the level of the final amputation. Regardless of the selected level of amputation, a full-thickness myocutaneous flap to cushion the areas of highest pressure and shear should be present. In rare instances, free tissue transfer has been utilized to successfully salvage a functional joint level in the absence of adequate local soft-tissue coverage (Figs. 5-A and 5-B). A fracture proximal to the lowest practicable amputation level should be appropriately stabilized and should not, by itself, be considered an indication for a more proximal amputation.

Despite the increased number of complications that arise from performing an amputation through the zone of injury, the benefit of preserved post-amputation length usually outweighs the increased risk of wound complications and heterotopic ossification. The LEAP study suggested that atypical flap coverage does not increase the rate of wound complications. Skin grafts, soft-tissue expanders, and tissue transfer are all methods that have been successfully utilized to maintain post-amputation length. While successful results can be achieved with these methods, it is often at the cost of delayed prosthetic fitting and numerous revision operations to achieve the desired result.

An alternative that can be used to salvage length in very select cases is to perform an initial dermatomal harvest of skin that is degloved at the initial debridement and apply a primary skin graft over exposed muscle. This should be performed only in rare instances as we do not advocate definitive wound closure at the time of the index procedure. When considering the recommendations listed above, surgeons must still carefully weigh the risks associated with preserving limb length as they may adversely affect the ultimate functional outcome. In short, limb length should not be preserved at the expense of creating a nonhealing, marginal, or painful residual limb.

**Specific Amputation Levels**

**Lisfranc, Chopart, and Syme Amputations**

Amputations through the foot and ankle can be considered in cases of severe forefoot trauma when the hindfoot plantar skin and soft tissues have been spared. The Lisfranc disarticulation removes the forefoot through the tarsometatarsal joints. The bases of the second and fifth metatarsals should be left in order to preserve the transverse arch of the foot as well as to leave the insertion of the peroneus brevis intact. The tibialis anterior and peroneus longus tendons must also be preserved carefully. The Chopart amputation is performed through the talonavicular and calcaneocuboid joints. In this procedure, all of the ankle dorsiflexors are transected and the surgeon must make a diligent effort to perform a proper tendinous reconstruction in order to counteract the overpowering triceps surae. The Syme disarticulation is performed through the tibiotaral joint with removal of the malleoli, in the presence of a healthy undamaged heel pad and normal posterior arterial flow. The heel pad must then be maintained directly below the distal part of the tibia to avoid painful instability.

Potential benefits of these levels include their long lever arm and the potential ability to continue to bear weight and walk for short distances without the use of a prosthesis. Despite these benefits and the generally good results following transmetatarsal amputations, substantial limitations associated with difficult prosthetic fitting and the severe disruption of the musculotendinous balance of the foot are common. With the Lisfranc and Chopart amputations, a refractory equinovarus deformity frequently develops despite efforts to rebalance the foot. With the Syme amputation, it is important to maintain...
the heel pad directly beneath the residual tibia. One method of accomplishing this is to perform a tenodesis of the Achilles tendon to the posterior aspect of the distal part of the tibia as described by Smith et al. In addition to the difficulties with the heel pad, multiple studies have demonstrated the inability of many individuals with a Syme amputation to bear full weight...
through the residual limb without a prosthesis. A more proximal transtibial amputation should be considered and discussed with any patient who has sustained severe foot and ankle trauma as it generally provides a good functional outcome.

**Transtibial Amputation and Knee Disarticulation**

The transtibial amputation is the most common amputation performed for trauma patients and has, in general, been associated with the best functional outcomes. Individuals with a transtibial amputation have a high rate of prosthetic use and frequently consider themselves only minimally or not disabled. Their gait is minimally disturbed, and less energy is necessary for walking when the knee has been retained.

When the amputation described by Burgess et al. is performed, it is important to consider the residual limb length. Two and one-half centimeters for every 30 cm of height should be maintained if the injury pattern allows length to be determined by the surgeon. This usually equates to 12.5 to 17.5 cm of residual limb length, and erring on the side of creating a longer residual limb is usually indicated when soft-tissue coverage is adequate. Special attention to the fibula on the preoperative radiographs and in the operating room usually allows detection of tibiofibular instability. When instability is present, stabilization should be performed either proximally or distally. A bone-bridging synostosis (discussed in greater detail later) can be utilized to stabilize the fibula distally. In our experience, the extended posterior myofasciocutaneous flap described by Assal et al. provides excellent anterior-distal soft-tissue coverage at the expense of relatively frequent edge necrosis and minor wound complications. This extended flap places the suture line of the amputation at the anterior aspect of the residual limb. There is no anterior skin flap distal to the level of the tibial bone cut.

When performing a transtibial amputation with utilization of the extended posterior flap, we carry out a myodesis of the posterior musculature to the anterior aspect of the tibia. With use of two parallel drill-holes in the anterior aspect of the tibia, a number-5 nonabsorbable suture is utilized in a laterally buried horizontal mattress fashion to secure the myofascial flap over the distal and anterior aspects of the bone end. Additional number-1 or 0 sutures are placed in a simple or figure-of-eight fashion approximately 4 to 5 cm proximal to the end of the bone where the distal myofascial flap terminates to reinforce the myodesis by anchoring it to the anterior tibial periosteum. After this, the fasciocutaneous flap is further secured medially and laterally to the anterior crural fascia, and finally skin closure is performed.

The knee disarticulation was originally described in the pre-anesthetic era as an alternative to transosseous amputation. This was ideal at the time because it could be performed quickly with low blood loss due to the absence of bone cuts. Historically, the residual limb was covered with only subcutaneous tissue and skin, but this quickly fell out of favor because the thin coverage resulted in poor tolerance of a prosthesis. Its popularity has since increased among experts because of the development and utilization of a posterior myofasciocutaneous flap that appropriately pads the residual limb. Despite the increased popularity and improved outcomes of the knee disarticulation, the LEAP study recently cast a negative light on through-the-knee amputations after its findings indicated that patients with such an amputation had the slowest walking speeds and the least self-reported satisfaction. This result may be related to the poor soft-tissue coverage with these amputations. The study authors indicated that at least twelve of eighteen limbs undergoing through-the-knee amputation were lacking any gastrocnemius muscle for distal coverage, leaving only subcutaneous tissue and skin for coverage, which ostensibly led to poor prosthetic tolerance. Recent improvements in prostheses have also made this level more appealing, with an improved ability to compensate for the obligatory asymmetry of the heights of the centers of knee rotation between the sound limb and the limb with the through-the-knee amputation.

**Transfemoral Amputation, Hip Disarticulation, and Hemipelvectomy**

The loss of the knee following a transfemoral amputation results in a less efficient gait and increased energy expenditure during walking, ultimately translating into Short Form-36 (SF-36) scores that are lower than those for patients with a more distal amputation. At this proximal level, it is critical to perform a biomechanically sound amputation in order to minimize the inefficiency of the gait. The adductor myodesis is the most critical step toward achieving this goal. Gottschalk and Stills reported that the loss of the adductor magnus insertion from the distal part of the femur leads to a 70% loss of the adduction moment on the femur. This leads to progressive muscle atrophy and decreased thigh strength and allows a relatively unopposed abduction moment, gradually causing a lateral drift of the residual femur within the soft-tissue envelope. When this occurs, the remaining hip musculature is unable to adequately support the pelvis, which decreases gait efficiency even further. For this reason, it is imperative that an adductor myodesis be performed during a transfemoral amputation. We advocate an additional myodesis of the medial hamstrings to enhance the postero medial forces counterbalancing the strong abductors and hip flexors. Myoplasty of the quadriceps apron (the retinaculum and tendinous expansion of the distal quadriceps musculature proximal to the patella) and biceps femoris is then performed to maximize padding and create a cylindrical, rather than a conical, distal part of the residual limb.

Hemipelvectomy is fortunately rarely required and are amputations of last resort. Historically, the functional outcomes and capacity for walking have been poor after amputations at these levels, but the development of modern suction-fit prosthetics has allowed good functional outcomes in some patients. General rules regarding nerve management and padding apply to both levels. Preservation of as much of the hemipelvis as the soft tissues permit (e.g., portions of the iliac wing or ischium) may improve sitting balance and prosthesis force transmission and suspension following nearly total hemipelvectomy.
Figs. 6-A and 6-B Standing scanogram radiographs demonstrating the limb-alignment benefits of length preservation with a transfemoral amputation and a stable adductor myodesis. **Fig. 6-A** A patient with a long residual limb after a right transfemoral amputation, with nearly anatomic femoral alignment and a stable myodesis. **Fig. 6-B** A patient with a mid-length left transfemoral amputation, with lateral drift of the distal part of the femur secondary to an abduction deformity and a failed myodesis.
Postoperative Care

Multiple, sometimes conflicting management techniques and philosophies exist with regard to the postoperative dressing after a trauma-related amputation. The most commonly used techniques include utilization of soft or rigid dressings and the immediate postoperative prosthesis (IPOP). Each of these has advantages and disadvantages, but when utilized appropriately all are currently acceptable as no method has proven superior with regard to preventing complications or improving outcomes. Regardless of the technique chosen, it is imperative that gentle balanced compression be applied to the residual limb to control swelling, decrease pain, and promote a stable limb volume. We advocate early utilization of elastic shrinkers as soon as postoperative drains are removed. Regardless, a transition from postoperative dressings to elastic shrinkers is warranted as soon as the surgeon is satisfied with the initial wound-healing in order to further stabilize the limb volume and ready the limb for prosthetic wear. In addition, early physical therapy should be initiated to prevent contracture formation.

Soft and Rigid Dressings

Trauma-related amputations are frequently performed within the zone of injury, and atypical soft-tissue coverage is relatively common. The use of a soft dressing allows frequent non-labor-intensive dressing changes and close surveillance of these complication-prone wound closures. Rigid dressings have frequently been utilized in the management of transtibial and more distal amputations. The efficacy of this bandage lies in its ability to control edema, prevent joint contractures, and improve pain control. Despite multiple studies that have shown a trend toward better wound-healing with a rigid dressing, the soft dressing is still frequently used and recommended after trauma-related amputations because of the ease of wound inspection, the improved ability to mobilize the patients early, and the decreased risk of pressure ulceration, particularly over the patella.

Immediate Postoperative Prosthesis

The immediate postoperative prosthesis (IPOP) was originally proposed shortly after World War I and has been used and modified following World War II, the Korean War, and the Vietnam War. The premise of the IPOP is to immediately fit patients with a temporary prosthesis following an operation. Benefits of the IPOP have been demonstrated mainly in a non-trauma population and include improved psychological outlook, less perceived loss of function, shorter hospital stays, fewer revision operations, and a faster time to initial prosthetic fitting. Despite these advantages, IPOP use is limited in the trauma population because of expense and time requirements as well as the very real concerns of achieving adequate wound-healing and the early detection of infection and associated injuries that often preclude early mobilization.

Outcomes of Treatment

Functional Outcomes

In 1993, Pierce et al. questioned the concept that individuals with a trauma-related amputation routinely had good functional outcomes when they discovered that 51% of their sixty-one patients experienced anatomic or physical problems related to the amputation. These data were supported by the findings of Smith et al., who indicated that individuals with an isolated transtibial amputation scored significantly lower than age-matched individuals in the SF-36 categories of physical functioning ($p = 0.0001$) and role limitations ($p = 0.0004$) because of physical health problems. Despite these findings, an optimistic attitude about the outcomes of trauma-related amputations persisted, as was made readily apparent by the LEAP study hypothesis that patients who underwent amputation after severe lower-extremity injury would have better outcomes than those who underwent limb salvage. The study, however, did not confirm this and actually demonstrated that severe disability was common following above-the-ankle amputations due to trauma.

The LEAP study continues to heighten the awareness that amputation is not always the best treatment for severe lower-extremity injuries. The study demonstrated in a prospective fashion the short-term complications that accompany this procedure. Long-term follow-up studies have also indicated that individuals with a trauma-related amputation have long-term residual limb, phantom-limb, back, and joint pain. Low-back pain appears to be the most common chronic disabling pain experienced by individuals with an amputation. Smith et al. reported that 71% of their patients experienced back pain following a unilateral amputation. The study subjects indicated that the back pain was significantly more bothersome than their phantom-limb pain ($p \leq 0.05$). The frequency of back pain was also significantly higher after above-the-knee amputations ($p \leq 0.05$).

In addition to the chronic pain experienced by individuals who have had an amputation, the most concerning health issue in this population was described by Robbins et al. after a review of the long-term health outcomes associated with war-related amputations. They reviewed multiple studies that indicated that individuals with an amputation were at a significantly higher risk of developing and dying of cardiovascular disease than a control group of matched patients ($p < 0.05$).

Another area that should be evaluated is the ability of patients to return to a productive vocational life following a trauma-related amputation. Substantial evidence suggests that, although the majority of individuals with a trauma-related amputation are able to return to work, they frequently require a change in their occupation following their injury.

Pain Management

There is a distinct association between acute postoperative pain and chronic amputation-related pain. Patients who report the greatest acute phantom-limb pain are more likely to continue to be affected by phantom-limb pain at both six and twelve months following the operation. Consequently, attempts have been made to reduce the early pain experienced following an amputation. The long-term positive impact of these techniques is currently being debated, yet the short-term benefits of current anesthesia techniques include increased patient com-
fort, a decreased narcotic requirement, and slightly earlier mobilization. The goal of these anesthesia techniques is to prevent central neuroplastic changes from occurring through the use of preventive multimodal analgesia. These modalities are aimed at various stages of the nociceptive pathways and include anti-convulsants such as gabapentin and pregabalin, nonsteroidal anti-inflammatory drugs, local nerve-sheath injections of anesthetics, alpha-2 agonists, ketamine, opioids, preemptive epidural injections, and regional nerve blocks.[110] We believe that the complexity of performing these various anesthesia techniques, the multiple classes of medications, and the often chronic nature of amputation-related pain suggest that a surgeon should consult a pain specialist either prior to or shortly following an amputation. A cooperative effort between the pain specialist and the surgeon will ensure that causes of pain that can be relieved with surgery are addressed while long-term chronic pain is also treated.

Psychosocial Impact of Amputation
The findings of the LEAP study group have heightened the awareness of the psychosocial disability that individuals experience after a lower-extremity amputation[111]. In that study, 48% of 505 patients who had sustained severe lower-extremity trauma had a positive result on screening for a psychological disorder at three months after the injury. In this same cohort, 42% of 452 patients remained positive for a psychological disorder at twenty-four months after the injury.[111] Trauma-related amputations represent a life stressor for even the highest functioning individuals. Trauma patients generally do not get time to consider their situation, and often their first thought or discussion regarding amputation occurs when they awaken from anesthesia with the loss of a limb.

In an attempt to address all of these necessary components of rehabilitation after an amputation, including the psychological needs, the United States military has established Amputee Care Programs during the current conflicts as well as during and after all previous conflicts starting with World War I.[112] The establishment of these programs was an attempt to standardize the care as well as pool the resources and expertise in the multidimensional care of military personnel who had had an amputation. The current program was developed with the recognition of the complex multifaceted aspects of a patient’s recovery, and efforts were made to provide support in each of these areas while utilizing a sports medicine-based, activity-oriented rehabilitation program.[113]

While the implementation of such comprehensive programs is not realistic at all medical trauma facilities, many already exist in one form or another, and those existing inpatient rehabilitation programs can be utilized for individuals with a trauma-related amputation. Pezzin et al.[114] demonstrated that patients who were discharged to inpatient rehabilitation after a trauma-related amputation had improved health and vocational prospects.

Complications Following Trauma-Related Amputations
Despite attention to perioperative and operative details, amputations due to trauma can be fraught with complications. These can range from minor dermatologic problems to major complications requiring multiple return trips to the operating room and possible loss of residual limb length. In a recent investigation by the LEAP study group, >85% of 520 patients who had severe lower-extremity trauma had a complication[115]. Nearly half of 149 patients who were treated with amputation had either a wound infection or wound necrosis. This supports the early finding of Pierce et al.[116] that half of their sixty-one patients who had undergone a trauma-related amputation had a postoperative complication. The most common complications include symptomatic neuromas and phantom and residual-limb pain[117]. Less frequently reported short and intermediate-term complications include bone spurs, heterotopic ossification, and failure of a myodesis procedure[118]. In the long term, most amputations are complicated by some degree of chronic residual-limb, phantom-limb, and low-back pain as well as degenerative joint disease of both ipsilateral and contralateral joints.[119-121] As noted, patients who have had an amputation are also at substantial risk of developing cardiovascular disease[122].

Approach to Surgical Complications and Revision Amputations
The long-term follow-up of individuals with a trauma-related amputation throughout and after their initial rehabilitation may identify a substantial proportion with potentially correctable symptomatic complications, including bone spurs, heterotopic ossification, symptomatic neuromas, failure of a myodesis, wound complications, and redundant soft tissue in the form of so-called dog ears (redundant soft tissue at the wound edge that protrudes and is cosmetically unappealing and may result in pain or ulceration within a prosthetic socket). Under these circumstances, it is imperative to maintain a close working relationship with both the patient and his or her prosthetist. Exhaustive nonoperative treatment options should be used for the early management of all of these complications, with the exception of failure of a myodesis. Prosthesis and socket adjustments, padding, and gait training should all be maximized prior to operative intervention.

Operative intervention may be warranted when functional improvement ceases to progress, the patient is still not satisfied with the current use of the prosthesis or with his or her overall function, and a cause of symptoms for which an operation is indicated is identified. In the majority of situations, previous amputation incisions should be utilized and the surgical planes should be carefully developed. Particular attention should be paid to the myodesis. With certain complications such as so-called dog ears, superficial neuromas, or superficial infections, the myodesis may not have to be taken down in order to address the problem. If the myodesis is taken down, preservation of the muscle fascia must be accomplished in order to perform an adequate revision myodesis. Careful dissection through the scarred tissue planes is performed until anatomically identifiable structures are seen. At this time, revision traction neurectomy, revision myodesis, or excision of heterotopic bone can be carried out. In our experience, dramatic pain relief and increased prosthetic wear following operative treatment of complications is common.
Controversies and Future Directions

Bridge Synostosis (Modified Ertl) and Transtibial Amputation

During World War I, Ertl developed and popularized a technique for transtibial amputation that created a distal synostosis between the tibia and the fibula in order to provide a more stable, broad, end-bearing residual limb. Although Ertl’s theories regarding the sealing of the medullary canal and the restoration of so-called normal bone physiology have been largely discarded, his concept has been broadly utilized and frequently modified since that time. There is substantial controversy surrounding this procedure, and the functional benefit of the technique remains uncertain. In 2006, Pinzur et al. reported the results of a study that suggested that patient-perceived functional outcomes were improved by a bone-bridging procedure. However, in a more recent study comparing the patients in that series with patients in the United States, Pinzur and colleagues were unable to demonstrate an advantage over the traditional transtibial amputation described by Burgess et al.

To our knowledge, there has been no long-term review of the complications unique to this procedure, which include symptomatic nonunion, malunion, bone-bridge dislocation, and implant-related complications (Figs. 7-A and 7-B).

Further study of the complication rates of these procedures as well as additional, ideally prospective, studies to determine if there is functional benefit of this procedure over traditional techniques must be conducted prior to advocating creation of a bridge synostosis as a preferred method of primary amputation.

Osseointegration

Osseointegration is described as structurally and functionally stable fixation and coexistence between bone and controlled synthetic components (usually titanium) providing lasting clinical function without rejection. Osseointegration has been in clinical use since the 1950s, but its application in amputation surgery was only begun in 1990. It is an experimental technique in which a titanium rod is screwed into a residual bone and then, often at a second surgery, is brought transcutaneously to allow prosthetic limb attachment. Osseointegration has not been approved by the United States Food and Drug Administration (FDA).

Potential benefits of osseointegration include easy and fast donning and doffing of the artificial limb, direct force transmission to the prosthesis, a proper fit every time that always remains in the same position, no restriction of the
proximal joint range of motion, and no socket or liner that may cause sweating, sores, and discomfort\textsuperscript{12,14}. Despite these suggested advantages, the concept of osseointegration remains experimental and is associated with substantial complications that have limited its use to date. The most frequent complications include superficial and deep infections, implant loosening, and periprosthetic fracture\textsuperscript{27}. Revision osseointegration surgery or revision to a conventional residual limb following failure of osseointegration frequently requires substantial shortening of the residual limb. The most concerning of these problems is the risk of infection, and continued research efforts are being devoted to developing methods of stabilizing the skin-implant-environment interface around transcutaneous implants\textsuperscript{12}.

**Overview**

Trauma-related amputations are relatively common but are infrequently performed by the majority of orthopaedic surgeons. For this reason, an involved and attentive surgeon is a necessity for optimal outcomes, and a well-performed amputation or revision amputation should always be considered a challenge for even an experienced surgeon. Although these procedures are associated with frequent complications and may lead to poor outcomes, adherence to proper operative techniques and the avoidance of well-documented technical errors can dramatically improve the ultimate functional outcome for the patient. While the treatment of severe lower-extremity trauma can be disheartening to both the patient and the surgeon, a successful result with dramatic functional recovery and a highly functioning individual can be equally rewarding.

**References**


