Application of the Orthoplastic Reconstructive Ladder to Preserve Lower Extremity Amputation Length

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Background: A primary goal in traumatic lower extremity amputation management is preservation of limb length. Energy expenditure during ambulation directly correlates with residual limb length, preserved limb segments, and stable joint preservation. An additional factor affecting limb function includes achieving adequate residual limb soft tissue coverage. This report describes techniques for achieving a stable soft tissue envelope to facilitate limb length and joint preservation.

Methods: A series of traumatic amputation cases with inadequate soft tissue coverage are reviewed. Concepts from the reconstructive surgery ladder were used to achieve residual limb soft tissue coverage and to preserve lower extremity amputation length.

Results: Soft tissue coverage was accomplished through a series of methods including delayed primary closure with assistance from an external tissue expander, use of acellular dermal regenerative templates combined with split-thickness skin grafting and negative-pressure wound therapy, use of biologic scaffolds such as extracellular porcine urinary bladder matrix combined with delayed skin grafting, and local pedicle flaps or adjacent tissue rearrangements and free tissue transfers.

Conclusions: The preservation of residual limb length in lower extremity amputations is crucial to optimize prosthetic fitting and to obtain the maximal functional outcome. A series of cases are presented that outline soft tissue coverage options for preserving maximal residual limb length. Applying various concepts from the reconstructive ladder may allow for viable soft tissue coverage to maximize functional outcome.

Key Words: amputation, soft tissue, length, energy, salvage

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Since the Global War on Terror commenced in 2001, more than 1200 US Service Members have sustained more than 1600 amputations.[1] Knowledge of amputation management is critical to ensure the best possible outcome.[2] A primary goal in lower extremity amputation management is limb length preservation and the maintenance of viable joints.[3] Furthermore, energy expenditure during ambulation directly correlates with residual limb length, preservation of functional segments, and preservation of a stable joint.[4,5] These tenets directly contribute to the resumption of a more normal gait pattern, increased functional capacity, and decreased energy expenditure.[6] The ability to preserve limb length, functional segments, and joints is significantly dependent on achieving sufficient soft tissue coverage. The reconstructive ladder serves as a guide for reconstructive surgeons to use the best possible tactic for soft issue coverage, and its utilization requires careful assessment of the extent of soft tissue defect, its related constraints, and ultimately the desired functional requirements or goals of the reconstructed residual limb.[7]

The aim of this article was to illustrate through several case reports the application of the reconstructive ladder for preserving residual limb length in lower extremity traumatic amputations. Using this series of amputation cases, the modalities used to achieve soft tissue coverage for preservation of limb length are presented. Concepts from the reconstructive ladder were used to determine the optimal method for achieving adequate soft tissue coverage and thus preserving residual limb length.[8]

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CASE REPORTS

Case 1

A US Soldier injured by an improvised explosive device blast, sustained multisystem trauma including a traumatic transtibial amputation (Fig. 1A). The level of bony amputation was distal to the tibia tubercle, and his knee extensor mechanism was intact. However, the zone of soft tissue injury extended well above the knee joint. There was inadequate soft tissue to achieve primary closure, to perform an effective myodesis, myoplasty, or to provide a well-padded residual limb. Treatment options included revising the amputation to a knee disarticulation or transfemoral amputation. However, to preserve length, limb segment, and a functional joint, the patient underwent soft tissue coverage with a latissimus free flap, followed by split-thickness skin grafting (STSG) (Fig. 1B).

The patient ultimately progressed to ambulation with a functional below-knee amputation without assist devices.

Case 2

A US Marine sustained bilateral above-the-knee amputations secondary to an improvised explosive device. After serial debridements and eradication of an angioinvasive fungal infection, a stable myodesis and myoplasty was performed with remaining viable healthy muscle (Fig. 2A). However, there was significant skin loss. Dermal coverage was achieved using a combination of therapies including initial application of a biocomposite dermal substitute (Integra Meshed Bilayer Wound Matrix; Integra Lifesciences Inc) and negative-pressure wound therapy (NPWT) (Fig. 2B), followed by delayed STSG (Fig. 2C). The biocomposite dermal substitute was used to provide a dermal layer that could withstand the sheer forces associated with prosthetic wear. The patient is able to stand and transfer with prosthetics and uses a wheelchair for primary mobilization.

Case 3

A 24-year-old marine sustained multisystem trauma including a left above-knee amputation (Fig. 3A). To facilitate closure, he underwent rotational skin mobilization combined with a dermal substitute bovine collagen layer application and subsequent STSG

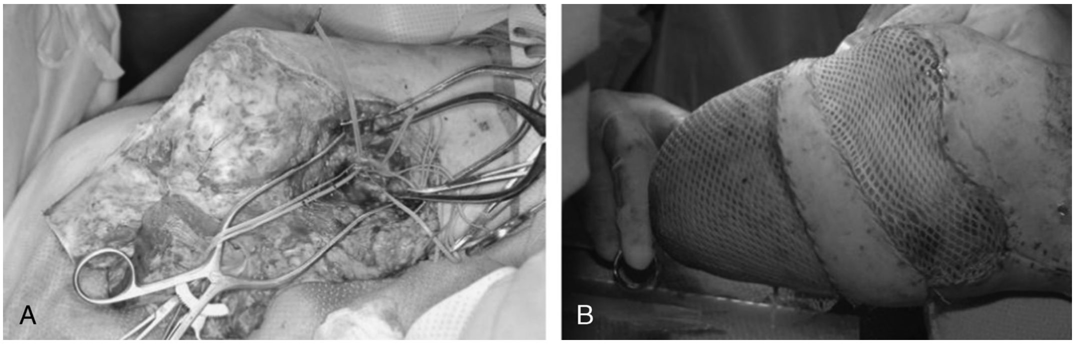

FIGURE 1. A, Use of free flaps and skin grafting. This wounded soldier sustained a traumatic below-knee amputation with significant soft tissue loss about his right knee and residual proximal tibia from a blast injury. B, A latissimus free flap combined with STSG allowed for soft tissue coverage over the tibia and knee.

FIGURE 2. A, A patient's left lower traumatic above-knee amputation managed with serial irrigation and debridements. Once amenable, a stable myodesis and myoplasty was performed. B, To recreate a subdermal layer, an acellular dermal matrix was applied. C, An STSG was applied to manage the loss of the cutaneous layer.

FIGURE 3. A, Above-knee amputation from a blast injury with significant skin and soft tissue loss. B, C, The previously mentioned patient was treated with rotation and approximation of atypical skin flaps to facilitate closure, followed by STSG of areas which cannot be closed primarily.

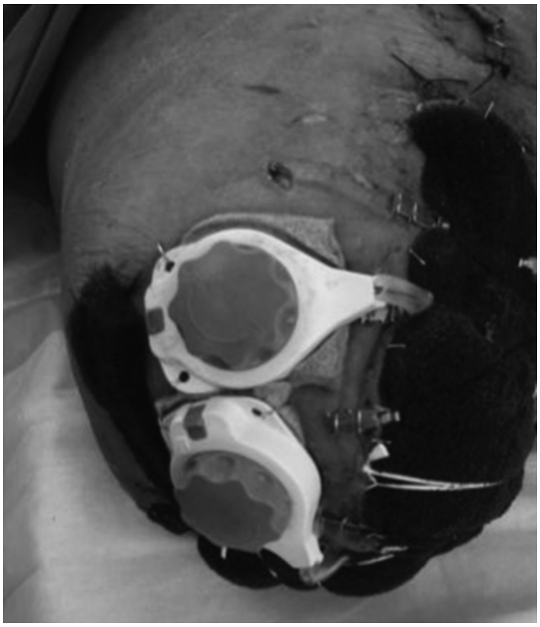

FIGURE 4. A patient with an above-knee amputation with significant soft tissue loss. A Dermaclose device was used to assist in coverage, avoiding the need for flap coverage, grafts, or excessive shortening.

(Fig. 3B). Preservation and utilization of all available soft tissue facilitates primary closure and approximation of native skin that can withstand the sheer forces associated with prosthetic wear. He has progressed to ambulation with above-the-knee prosthesis and ambulates without assistive devices.

Case 4

A 32-year-old soldier sustained bilateral above-the-knee amputations. There was inadequate dermal tissue available to perform primary closure. The patient did have adequate tissue to perform an effective myodesis and myoplasty. To facilitate limb soft tissue and dermal coverage, an external tissue expander was used (Fig. 4). The patient is able to ambulate with prosthetics, managing stairs with the use of 1 handrail.

Case 5

A 27-year-old marine sustained multisystem trauma including a very proximal right transtibial amputation (Fig. 5A). The extensor mechanism was intact; however, there was inadequate skin coverage over the residual limb. The patient did have adequate muscle to perform an effective myodesis and myoplasty. In this case, a porcine-derived biomatrix scaffold (Matristem Micromatrix and Matristem Surgical Matrix; ACell, Inc) was used to regenerate a suitable wound bed of granulation tissue (Fig. 5B) for staged STSG over the avascular retinaculum and exposed patellar ligament. Split-thickness skin grafting over this area would have likely failed secondary to the avascular nature of the available soft tissue. Once an amenable wound bed for skin grafting was evident, a STSG procedure was completed (Fig. 5C–E). The patient is able to ambulate with a below-the-knee prosthesis without assist devices.

DISCUSSION

Preservation of residual limb length in lower extremity amputations is critical for both optimizing prosthetic fitting and functional ambulation. Longer residual limb length, joint preservation, and adequate distal residual length have all been shown to decrease an amputee's energy requirements during functional ambulation. Waters et al reported significantly higher energy requirements during prosthetic ambulation for transfemoral amputees compared to transtibial amputees. Furthermore, their group demonstrated that conversion of a transtibial to a transfemoral amputation resulted in an increase of energy expenditure by 25% to 65% above the patient's prior baseline.[4] Additionally, in transfemoral amputees, the residual femur length substantially influences a patient's temporospatial and kinematic gait outcomes, typically slowing self-selected gait speeds with shorter transfemoral lengths.[9]

Preservation of residual limb length requires 2 important considerations: (1) the management of underlying residual bony segment and (2) the management of its associated soft tissue envelope. In most cases, residual bone is not the main limiting factor determining the potential functional level of the residual limb to be preserved. However, bone should be preserved at the most distant level permissible given the constraints of the soft tissue envelope reconstruction considered. In certain cases, fracture stabilization within the amputated limb to preserve amputation bone length may add additional complexities to soft tissue coverage and residual length salvage (Fig. 6). For example, Gordon et al recently retrospectively analyzed 37 combat amputees with ipsilateral fracture stabilizations within their amputated limbs—32% of cases which had fixation of their distal retained osseous segment. Although high infection and heterotopic ossification rates were seen in this study, the amputees had acceptable functional ambulation outcomes and tolerances of light to moderately heavy work as evidenced by average Tegner scores of 3.3.[10,11]

With respect to mangled extremity trauma, the soft tissue envelope is usually the most challenging consideration for potential residual amputation salvage versus more proximal revision amputation.[12] A major tenant in amputation surgery is the provision of an adequately padded, durable soft tissue surface suitable for prosthetic fitting and wear. Thus, not only is care in the handling and preservation of available soft tissue crucial, but one must also preserve appropriate muscle balancing for achieving optimal functional results. Our group has developed approaches to preserve amputation length based on the reconstructive principles outlined within the reconstructive ladder (Fig. 7).[13–15]

The traditional reconstructive ladder provides a guide for surgeons to use simpler techniques and advancing upward to more complex reconstructive techniques based on the need and degree of soft tissue injury and available donor tissue sources.[13–15] Techniques such as local wound care, primary closure, skin grafting, local skin flaps, pedicles flaps, and free flaps are all important components for definitive soft tissue coverage. More recently, our group has developed "hybrid reconstruction techniques," coupling regenerative medicine modalities in addition to the standard reconstructive ladder techniques to better address composite tissue defects of the extremities and amputations (Fig. 8). Specifically, use of dermal regenerative templates and extracellular matrices as well as adipose and/or muscle-derived stem cell therapies in conjunction with skin grafting, local, regional flaps, or free tissue transfers have been applied to aid in reconstruction and preservation of residual limb lengths in our amputee patient population. In addition to various regenerative medicine modalities, nanotechnologies have been incorporated into our amputation wound management. Our reconstructive team frequently uses dressings that release nanocrystalline silver crystals that can eradicate bacteria and decrease infection rates in severely traumatized amputation wounds.[16] Studies suggest that this technology alters wound inflammatory events and facilitates the early phase of wound healing while also reducing rates of wound infection.[17]

Our team strives for maximum amputated limb length salvage in today's Wounded Warriors with the end-state and goals in mind of attempting to enhance their future recovery, rehabilitation,

FIGURE 5. A, Right transtibial amputation revealing significant soft tissue loss with preservation of the extensor mechanism. B, Right transtibial amputation after serial irrigation and debridements. A successful myodesis and myoplasty was performed. However, there was inadequate tissue coverage over exposed retinaculum and extensor mechanism. A healthy bed of granulation tissue was formed over the hypovascular structures using acellular matrix and NPWT. C, Right transtibial amputation managed with STSG. D-E, Right transtibial amputation approximately 3 months after STSG.

and performance during period of expected remaining lifespan. These warriors are typically young adults aged 18 to 30 years who are expected to have a lifespan that extends 50 to 60 more years from now. As the wounded warriors age, a 25% to 65% increase in energy expenditure above baseline could be the difference between a mobile verses wheel-chair dependent 60 year old in the future.

Reconstructive Ladder

As a general practice, our group attempts to avoid terminal residual limb STSG as an isolated soft tissue stump coverage strategy (STSG). However, in certain injuries patterns, this treatment method is occasionally necessary to preserve limb length. Revision surgery as suggested by Wood et al, including excision of previously grafted skin, may be frequently necessary to avoid proximal joint removal. Consideration of STSG should outweigh the conversion to higher amputation functional levels just for skin coverage.[18] This technique has greatly decreased the need for free flaps and seems to be a safe and feasible option to preserve limb length.[19]

In cases where skin grafting is anticipated, our group has transitioned to the use of many of the dermal regenerates (ie, Integra) that had been initially developed for burn management. Most frequently we use a bilayer matrix wound dressing consisting of a primary layer of cross-linked bovine tendon collagen and glycosaminoglycan and a secondary layer consisting of a semipermeable silicone layer. This bilayer matrix controls water vapor loss, provides a flexible adherent covering, allows increased sheer strength, and seems to biodegrade for cell and capillary ingrowth.[20] It is typically used in conjunction with NPWT and is followed by an ultrathin STSG (12 μm) at approximately 2 to 3 weeks. The dermal substitute effectively recreates adequate subcutaneous tissue to allow for gliding or movement of the skin over the muscle and has been objectively demonstrated to provide elastic properties comparable to normal skin.[21] During the past 4 years, more than 300 patients have had a dermal regenerative matrix used to assist in soft tissue coverage.

Delayed primary closure using external tissue expansion has been described in multiple scenarios including fasciotomy[22] and complex wound closure.[23] Combined with NPWT, it is a dynamic version of the traditional vessel loop Roman sandal traction that is frequently used for management of difficult wounds (Fig. 9).[24] Our group has successfully used external tissue expansion (eg, Dermaclose) to facilitate

FIGURE 6. Anterior-posterior plain radiograph of a transtibial amputation managed with stabilization of the complex tibial plateau fracture and femoral diaphysis fracture in the amputated limb. Management of the fractures in the residual limb facilitates preserving limb length.

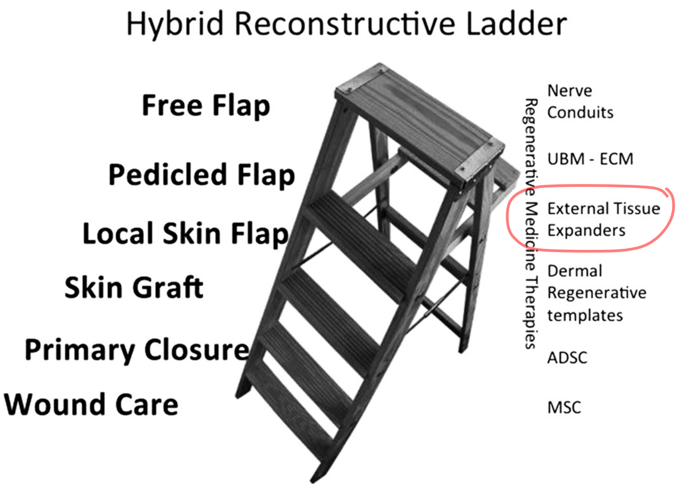

FIGURE 8. The hybrid reconstructive ladder uses techniques such as dermal regenerative templates, external tissue expanders, extracellular matrices, and nerve conduits to achieve the most functional residual limb.

wound closure and preserve amputation length. These devices allow serial closure, typically during period of 1 to 10 days.[25] Tissue expansion has been previously described by Watier et al for the salvage of below-knee amputations.[26] In this study of 7 patients, the authors used internal tissue expanders an average of 92 days, achieved excellent or good outcomes in 6 of 7 patients and were able to preserve a below-knee amputation level.[26] We have used external tissue expansion on more than 45 patients in combination with NPWT. External tissue expansion has been primarily used in those patients who have adequate muscle coverage of their residual limbs to perform a myodesis as well as myoplasty but lack adequate dermal coverage. We have found that even in those patients who cannot be primarily closed the external tissue expanders decreased the wound volume so that other modalities, such as STSG, only have to be minimally used.

FIGURE 7. The traditional reconstructive ladder addresses skin coverage options in amputation care that range from local wound care up to a free tissue flap for coverage.

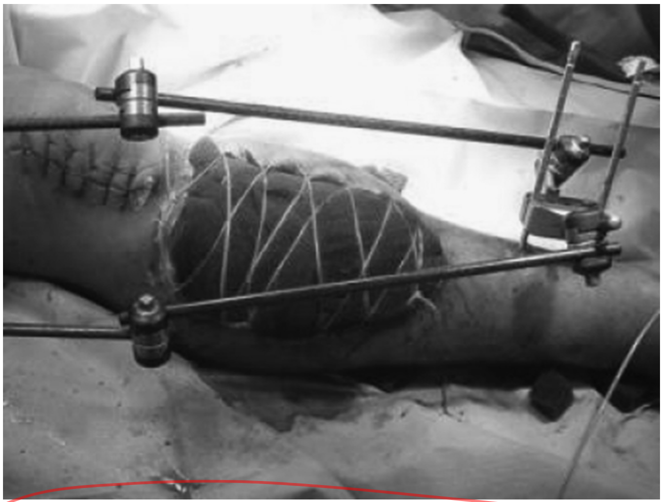

FIGURE 9. A patient with a more traditional ''Roman Sandal'' vessel loop skin traction over a wound lacking adequate posterior coverage. Although effective, this technique has not proved nearly as powerful as the Dermaclose device pictured in Figure 4.

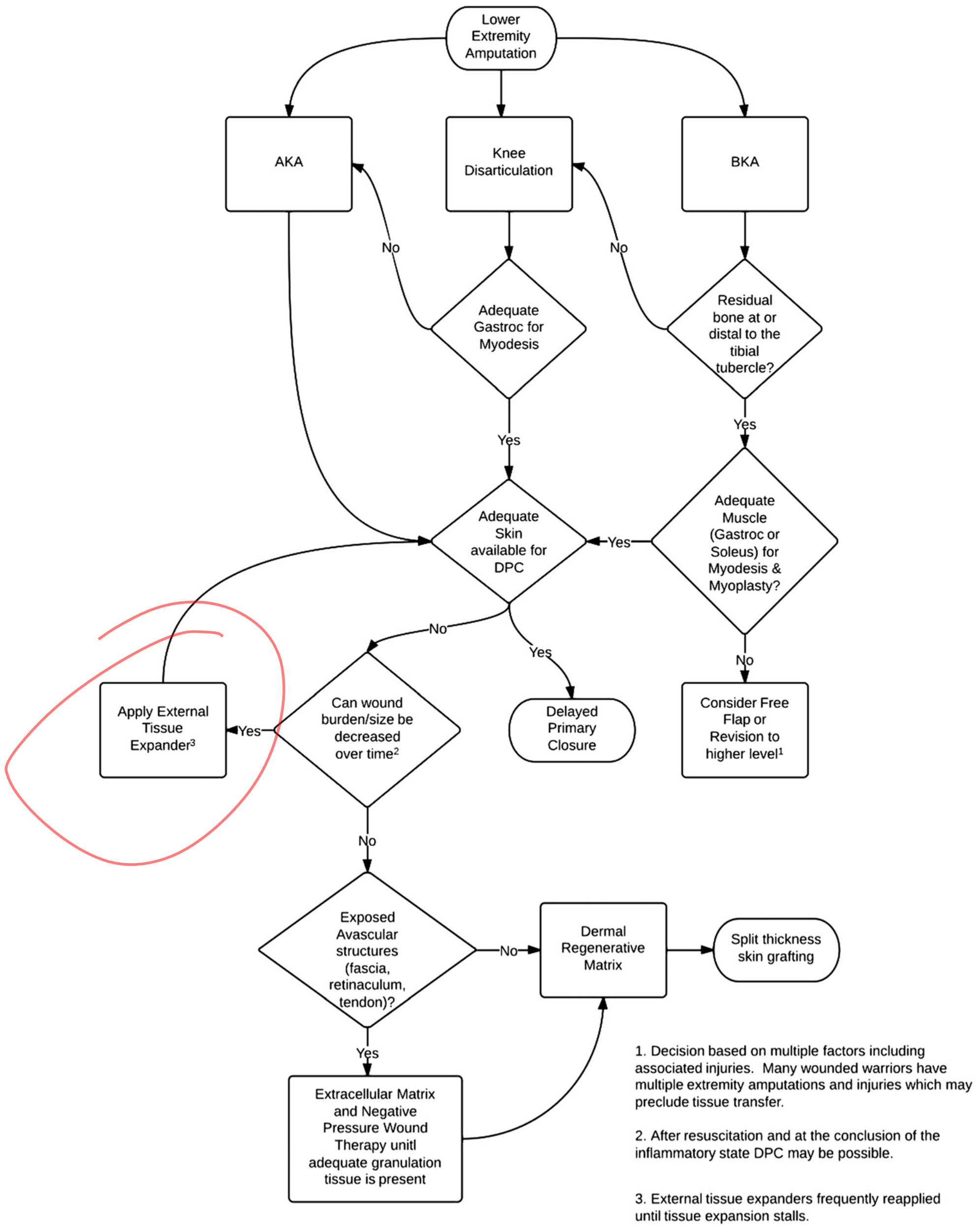

FIGURE 10. Decision matrix for orthoplastic management for lower extremity amputation length preservation.

There have been several case reports describing the use of NPWT to granulate areas of loss soft tissue such as over tendons, bone, and fascia.[27–29] An adjunct to NPWT that we have used is the use of extracellular matrices as a biologic scaffold. These biologic scaffolds have been described to attract adult stem cells[30] to the site of injury and converts them into active progenitor cells.[31] It also sets up non–cross-linked temporary scaffolding for tissue reconstruction, mimicking surrounding healthy tissue.[32] This scaffolding maintains an intact epithelial basement membrane[33] and typically results in a robust bed of granulation tissue. In the case example illustrated in the case series, STSG would have likely failed if applied directly to the retinaculum and patella ligament (Fig. 4A). In this case, 100% take of the STSG was achieved through the use of the extracellular matrix to form a healthy bed of granulation tissue before STSG. We have used the extracellular matrices in more than 50 patients for the purpose of limb length preservation.

To preserve bone and limb length, all viable soft tissue should be used. Atypical skin flaps, albeit in the zone of injury, can be rotated and approximated to facilitate primary or delayed primary closure. However, these types of closure have been associated with increased complications such as a higher infection rate and increased rates of symptomatic heterotopic ossification development.[34] Frequently, we encounter soft tissue that is of questionable viability. Although clinical judgment is the mainstay of management for assessing tissue that should be preserved versus debrided, our group has incorporated the use of intraoperative laser angiography (SPY; Novadaq Technologies Inc, Richmond, British Columbia, Canada) as an objective tool to predict tissue survival. This technology has multiple soft tissue applications[35] and has enhanced our ability to preserve tissue within the zone of injury, and in turn, preserve limb length.

In addition to the aforementioned strategies, more advanced techniques including local or regional flaps and free flaps may be necessary to facilitate lower extremity amputation length salvage and stable soft tissue coverage.[36–39] Traditionally, the latissimus free flap has been a workhorse flap for such purposes, although other microvascular flaps have been described for length preservation. Various muscle-based flaps including the latissimus flap, rectus flap, fasciocutaneous and perforator flaps such as the anteroloateral thigh flap,[40] the scapular and parascapular flap, and deep inferior epigastric perforator flap have all been used by our group for transtibial amputation salvage. Kasabian et al published the largest series with 22 patients and demonstrated that all patients were able to maintain a below-the-knee amputation.[36] We have used this technique in more than a dozen patients with satisfactory results.

CONCLUSIONS

The preservation of residual limb length in lower extremity amputations is crucial to optimize prosthetic fitting for the amputee to allow for their recovering maximal function with ambulation. Applying principles of the reconstructive ladder may facilitate the achievement of soft tissue coverage, a goal that is paramount in lower extremity residual limb management. Figure 10 is adapted from the reconstructive ladder and serves as a guide in our decision matrix. This case series describes soft tissue coverage options for preserving maximal residual limb length. The development of soft tissue management algorithms in caring for amputation cases, as reported in this study, may lead to better overall outcomes and success.

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