Journal of Hand Surgery Global Online 5 (2023) 81–86

Contents lists available at ScienceDirect

Journal of Hand Surgery Global Online

journal homepage: www.JHSGO.org

Surgical Technique

High-Transhumeral Amputation: Targeted Muscle Reinnervation and Soft Tissue Coverage With Pedicled Latissimus Dorsi Flap

Ersilia L. Anghel, MD, [*] Stephanie Radu, MCR, [†] Kelsi Krakauer, BS, [†] Jourdan Carboy, MD, [*] Kai Yang, MD, [*] Albert Chi, MD, [‡] Angelo Lipira, MD [*]

[*] Division of Plastic and Reconstructive Surgery, Oregon Health and Sciences University, Portland, OR
[†] School of Medicine, Oregon Health and Sciences University, Portland, OR
[‡] Department of Surgery, Oregon Health and Sciences University, Portland, OR

A R T I C L E I N F O

Article history:
Received for publication December 8, 2021
Accepted in revised form October 25, 2022
Available online November 18, 2022

Key words:
Computer learning
Targeted muscle reinnervation
Virtual rehabilitation

The introduction of targeted muscle reinnervation has improved amputation pain outcomes and the control of upper-extremity myoelectric prostheses. However, patients with proximal transhumeral amputation levels and soft tissue deficits present a unique challenge. Existing described targeted muscle reinnervation techniques in transhumeral amputees rely on recipient motor nerves from the biceps and triceps; however, these may be absent in patients with more proximal injuries. Here, we describe the use of the pedicled latissimus dorsi flap for both soft tissue coverage and additional motor targets in patients with high-transhumeral amputation with complex soft tissue deficits.

Targeted muscle reinnervation (TMR) is a procedure in which a transected nerve without the possibility of repair is transferred into a motor branch of a nearby muscle. Initially developed to provide additional detectable signals for myoelectric prosthetic control, it was subsequently demonstrated to decrease phantom and residual limb pain.[1–5] Evidence has suggested that TMR has a greater effect when performed at the time of amputation to prevent the establishment of corticospinal chronic pain pathways.[3]

Although upper-limb prostheses have existed for millennia, recently, there has been great technological progress. Devices now use myoelectric feedback and a neural processing system to perform more advanced tasks and movements. In myoelectric control, signals are generated by residual muscles in the amputated limb, which are transmitted to myoelectric surface electrodes. The degree of control and dexterity of these prostheses are largely dependent on the number and quality of signals that the residual limb can generate, which may be increased using TMR.

Effective techniques for TMR have been described for shoulder disarticulation as well as transhumeral- and transradial-level amputations. However, extensive traumatic soft tissue destruction may create a situation in which typical motor targets are not available for TMR, and, thus, tissue transfer is required to avoid conversion to a more proximal amputation. This report describes a technique for maintaining the transhumeral level of amputation in a patient with extensive muscle loss by transferring the latissimus dorsi muscle, which provided soft tissue coverage and 2 additional TMR motor targets. As a nearby, expendable large muscle with 2 motor branch targets available, the latissimus dorsi provides an ideal option for coverage and greater TMR options (Fig. 1).

Indications and Contraindications

Targeted muscle reinnervation can be performed at the time of initial amputation (primary TMR) or in patients with established amputations (secondary TMR). Primary TMR may be more effective in preventing phantom and residual limb pain and eliminates the need for additional procedures.[3] It allows the transfer of unscarred nerves with maximal length and facilitates earlier myoelectric prosthetic rehabilitation.[4] Any patient facing a major limb amputation who is healthy enough to undergo the procedure and does not have a proximal brachial plexus injury is a candidate.

Declaration of interests: No benefits in any form have been received or will be received related directly or indirectly to the subject of this article.

Corresponding author: Angelo Lipira, MD, Plastic and Reconstructive Surgery, Oregon Health and Science University, 3303 SW Bond Avenue, CH5P, Portland, OR 97239.

E-mail address: lipira@ohsu.edu (A. Lipira).

https://doi.org/10.1016/j.jhsg.2022.10.016
2589-5141/

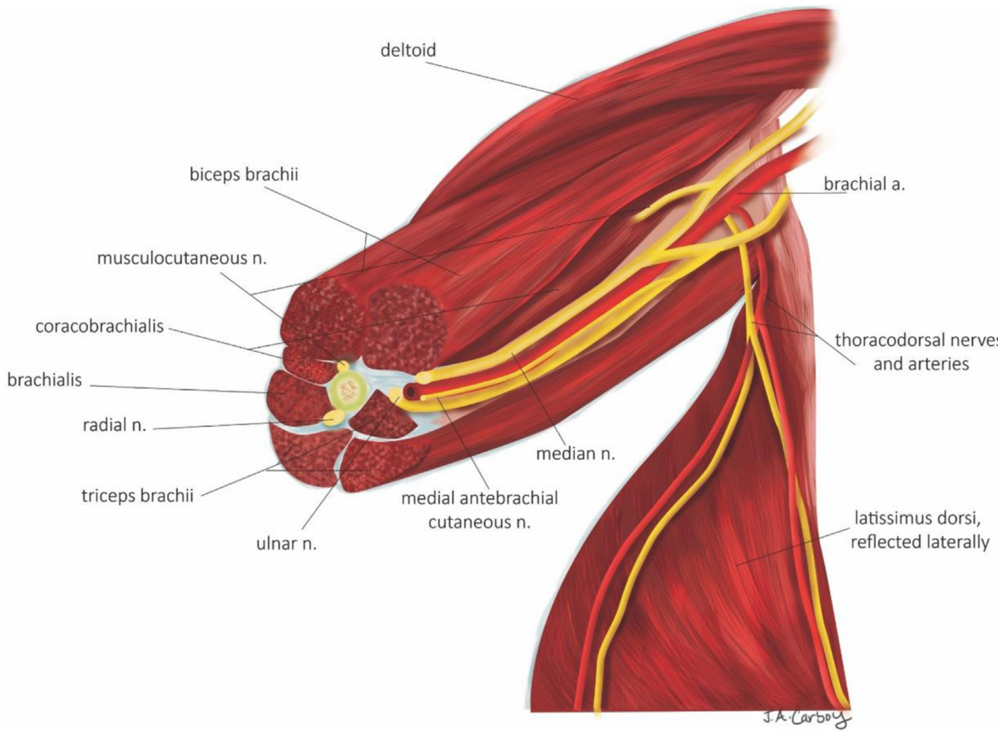

Figure 1. Anatomy of the arm's cross section at the transhumeral amputation level. This figure highlights the relevant surgical anatomy at the site of the transected humerus and demonstrates the anatomy of the thoracodorsal motor branch pertinent to the described procedure. a, artery; n, nerve.

Table
Nerve Transfer Anatomy for Standard TMR in Transhumeral Amputations*

Donor Nerve	Target Motor Nerve Branches
Median n.	Short head of the biceps
Distal radial n.	Lateral head of the triceps
Proximal radial n.	Long head of the triceps
Musculocutaneous n.	Long head of the biceps
Ulnar n.	Brachialis

n, nerve.
* This table outlines the nerve transfers used in standard TMR in transhumeral amputations. The donor nerve serves to reinnervate the target muscles severed in the amputation.

Surgical Anatomy

The pedicled latissimus dorsi flap is a workhorse flap for reconstruction of the upper extremities, breasts, thoracic region, and abdominal wall. It is versatile because of its long pedicle, large size, and superficial anatomic location, making dissection less complicated than with other options. The pedicled latissimus has a reach extending beyond the elbow or past the midline of the chest.[6] The muscle contours extremely well to irregular surfaces, making it an ideal coverage option for complex wounds. It is a flat, triangular-shaped muscle with multiple anatomic origins at spinous processes T7–12 and L1–5, the sacrum, and the posterior and middle iliac crests; furthermore, a small portion originates at the external surface of ribs 8–12. The triangular base converges into a single tendon to insert into the intertubercular groove and lesser tubercle of the humerus.

The latissimus dorsi is a Mathes-Nahai type V muscle, with the thoracodorsal neurovascular bundle being the primary pedicle. This bundle runs 2–3 cm medial to the lateral border of the latissimus and 2.5 cm below the inferior scapular border, entering the latissimus muscle on its deep surface. The thoracodorsal nerve arises from the posterior cord of the brachial plexus and is located inferolateral to the vascular pedicle. The nerve arborizes into 2–3 sizable motor branches, which can be used for motor targets in TMR (Fig. 2).[6]

In long-transhumeral amputations, either standard shortening of the humerus or angulation osteotomy of the distal aspect of the humerus can be performed to allow room for prosthesis suspension.[2] In transhumeral amputees who have not undergone TMR, there are two myoelectric control sites typically available over the biceps and triceps muscles. Two additional myoelectric control sites are also created by transferring the median and distal radial nerves into target muscles, typically the short head of the biceps and lateral head of the triceps, respectively.[7] The proximal aspect of the radial innervation of the long head of the triceps and the musculocutaneous innervation of the long head of the biceps are preserved.[7] The ulnar nerve may be transferred to the remnant brachialis muscle for a possible fifth control site (Fig. 2 and Table).[7]

It is not uncommon for short- or high-transhumeral amputees to have traumatically absent biceps, triceps, coracobrachialis, or brachialis muscles. This leads to a shortage of recipient motor sites and loss of soft tissue coverage, which, therefore, requires flap coverage. The latissimus provides soft tissue coverage and recipient motor nerves, thus addressing both the issues. Recently, Lu et al[8] described the use of the serratus anterior for soft tissue coverage and motor nerve recipients for TMR. Here, we describe the use of the latissimus dorsi flap for coverage of larger wounds in patients with transhumeral amputation, with the added benefit of providing 2 additional motor nerve recipients for TMR.

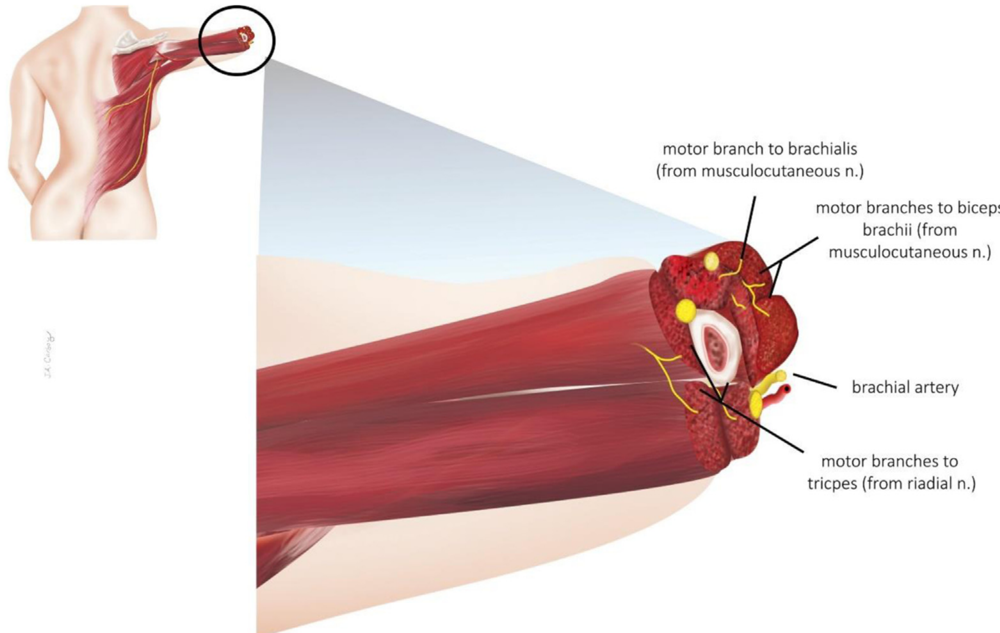

Figure 2. Recipient motor branch target options for coaptation at the transhumeral amputation level. The image of the left hand shows the branching pattern of the thoracodorsal nerve, which provides 2 recipient options for TMR. Shown on the right are motor branch recipients in the limb, which may be variably present in high-transhumeral amputations. The coracobrachialis is not shown; it is located more proximally and is not used when the biceps, triceps, and brachialis are available. n, nerve.

Potential Complications

Generally, upper-limb TMR is a well-tolerated procedure. In a review of 27 cases of upper-limb TMR, there were no clinically detectable hematomas, seromas, or infections despite extensive mobilization and dissection of soft tissue, although these cases did not involve flap coverage.[7] The other risks include neuroma and neuropathic pain despite TMR. However, TMR has been associated with a reduced need for pain medications.[9]

Although postoperative pain and prosthesis control are often improved with the use of TMR, it is not universally effective, and neuropathic pain can remain a challenging issue, as illustrated in the case example below. The other potential downsides are increased operative and anesthesia time as well as the need for additional incisions. The use of microsurgical techniques and coordination of multiple surgical teams may add to the complexity of the surgery and patient care. For patients, myoelectric prostheses are more expensive and have variable insurance coverage. Additionally, despite undergoing TMR, many patients ultimately never receive a high-end advanced prosthetic device. The well-documented complications of harvesting the latissimus dorsi flap include donor-site seromas and partial or total flap necrosis.

Despite these limitations, we believe that many patients facing transhumeral amputation with a soft tissue coverage deficit are well served by the use of the latissimus dorsi flap and TMR. The flap is an excellent option for wound closure and donor nerves when the biceps are traumatically absent. The use of the latissimus dorsi results in minimal function deficits. Since it involves superficial flap dissection, it has decreased risks compared with other options.[6]

Surgical Technique

The preoperative evaluation of humeral length, viable soft tissue, and locoregional flap options is critical for selecting the appropriate TMR pattern. For midhumeral amputations with inadequate soft tissue, the humerus can be shortened if the deltoid insertion is preserved. However, shortening beyond the deltoid insertion should be avoided, if possible, to allow humeral abduction and an adequate lever arm for prosthesis attachment. Flap coverage should be planned if necessary.[10] The intraoperative evaluation of viable muscle and motor targets may be performed during debridement procedures. Donor nerves (radial, median, ulnar, and musculocutaneous) are identified and tagged. In delayed TMR, Tinel signs should be sought before surgery and marked to guide dissection.

The landmarks for dissection of the latissimus dorsi are marked during surgery, with the patient awake: the posterior axillary line, anterior border of the latissimus muscle, tip of the scapula, and midline spine. In the operating room, the patient is positioned in the lateral decubitus position on a bean bag. The anesthesiologist must be informed to avoid long-acting muscle paralytics to allow for intraoperative nerve stimulation to identify recipient motor branches. Regional anesthetic blocks do not interfere with nerve stimulation and are encouraged for pain control and reduction of postoperative opioid requirements. Draping should allow exposure of the entire remaining limb, neck, back, and chest past the midline.

Next, attention is directed toward the identification of the major nerves and motor targets available for reinnervation. The median, ulnar, radial, and musculocutaneous nerves are dissected free from the surrounding tissue. In standard midhumeral amputations, the muscular innervation for the musculocutaneous nerve is preserved, and the preferred motor points are the short head of the biceps, brachialis, and lateral head of the triceps for reinnervation of the median, ulnar, and radial nerves (Table), respectively. In cases with more proximal traumatic amputations, other motor targets need to be identified. Anteriorly, the motor branch to the coracobrachialis can be identified by tracing along the muscular belly proximally, and the motor branch to the lateral triceps can be identified posteriorly by tracing along the radial nerve toward the shoulder. The motor branch to the pectoralis major muscle along the

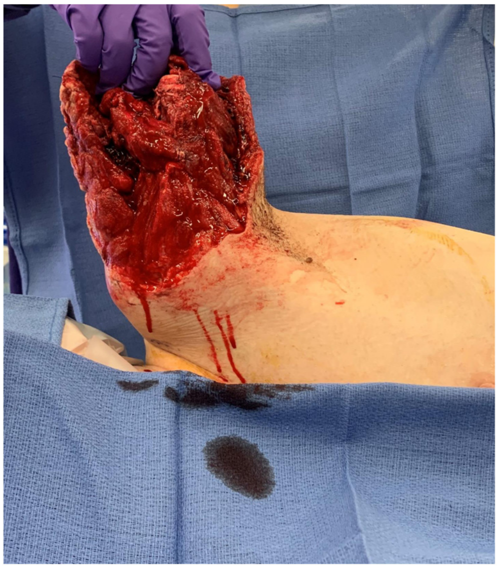

Figure 3. A high-transhumeral traumatic amputation injury with a soft tissue deficit and traumatic absence of biceps.

undersurface of the muscle belly could also serve as a motor target. The motor branch to the serratus muscle has been previously described as a motor target in the literature. However, denervation of the serratus may lead to a winged scapula, which would be detrimental to the use of prosthetic limbs.[10] The identification of motor branch targets is greatly facilitated through the use of intraoperative nerve stimulation, and the branches are marked with vessel loops.

The latissimus dorsi flap is elevated in a standard fashion in an inferior-to-superior and medial-to-lateral direction. The dissection is slowed as one proceeds superior to the tip of the scapula, and the neurovascular bundle is soon visualized on the undersurface of the muscle belly. The large serratus arterial branch should be identified and protected until the latissimus is completely isolated on its pedicle because this branch can perfuse the flap as a “lifeboat” in cases of inadvertent injury to the main pedicle. The thoracodorsal nerve is protected during elevation of the flap, and 2 large motor branches can be traced into the muscle belly with relative ease. These 2 motor branches provide excellent motor targets for TMR and, because of their superficial location in the muscle flap following inset, are easily detected later using EMG for myoelectric control. In transhumeral amputations, the axillary nerve is often intact, as is the deltoid. Therefore, it generally does not need to be reinnervated.

Donor nerves are trimmed back until healthy bleeding fascicular structures are visible, and recipient motor branches are divided as proximally as possible. The nerve ends are coapted using 8-0 nylon epineural sutures under 3.5× loupe magnification or an operating microscope. Fibrin glue is then applied over the coaptations. In the case presented below, the median and ulnar nerves were coapted to the 2 motor branches of the thoracodorsal nerve of the latissimus muscle. The musculocutaneous nerve was coapted to the motor point of the coracobrachialis muscle, and the radial nerve was coapted to the lateral triceps motor point. The latissimus muscle flap was then inset over a drain to cover the wound, and a split-thickness skin graft was applied over the muscle. Two 15-F channel drains were placed in the latissimus donor site.

Postoperative Management

A soft, noncompressive dressing is applied, and abduction of the shoulder is avoided to prevent traction on the fresh coaptations for the first 3 weeks. Patients receive standard 24-hour perioperative antibiotics and intraoperative irrigation of the wound prior to closure. However, in the event of highly contaminated traumatic amputations, some providers consider a longer postoperative antibiotic duration. The use of closed-suction drains in the immediate postoperative period may reduce the rates of hematomas or seromas; however, one must be mindful of excessive pressure on the flap or pedicle. Our postoperative pain control regimen involves aggressive use of regional anesthetic blocks and postoperative, scheduled gabapentin, acetaminophen, nonsteroidal anti-inflammatory drugs, and narcotics, as needed. We also encourage regional anesthetics before and during the operation. The skin graft and flap are evaluated on postoperative day 5. Unrestricted activities may resume once the flap and graft are well healed, usually 1 month after surgery.

Patients are able to use prostheses after edema has resolved, typically 3 months after surgery, and reinnervated muscle contractions usually become robust enough for fitting of TMR-controlled myoelectric prostheses between 4 and 6 months after surgery. Patients at our institution are offered the opportunity to engage in a virtual rehabilitation program, wherein they learn to activate their nerve transfers and practice controlling a virtual prosthetic arm, starting as early as 4 weeks after surgery.

Case Illustration

A 30-year-old right-handed woman presented to our level 1 trauma center with a complete traumatic amputation of the left upper extremity at the transhumeral bone level, with soft tissue loss above the bony amputation level, following a high-speed rollover motor vehicle collision (Fig. 3). Replantation was not possible because of severe segmental injuries to the amputated part and a completely absent elbow joint. After appropriate evaluation and stabilization of the trauma, she was taken to the operating room for initial debridement and intraoperative assessment. The brachial artery and vein were ligated. The bony level of the amputation was the distal humerus; however, both heads of the biceps brachii were traumatically absent, as were the medial and long heads of the triceps brachii. The proximal portion of the lateral head of the triceps as well as the coracobrachialis and deltoid were intact. The humerus was transected to a viable length while maintaining the deltoid insertion. Because of the extensive amount of muscle lost, a large soft tissue deficit remained (Fig. 3). The nerves were only gently debrided to maintain as much length as possible for TMR, and a negative-pressure wound therapy device was applied. The patient returned to the operating room for 3 additional debridements over a week because of the heavily contaminated nature of the wound and received appropriate antibiotics. The patient consented to this case illustration.

Discussions were held with the patient regarding options available to achieve the best possible outcome. She was highly motivated and desired to learn how to use an advanced myoelectric prosthesis. The potential benefits of TMR were of interest to her, and she elected to undergo pedicled latissimus dorsi flap coverage with TMR.

During surgery, her musculocutaneous nerve was transferred to the motor branch to the coracobrachialis, her radial nerve to the

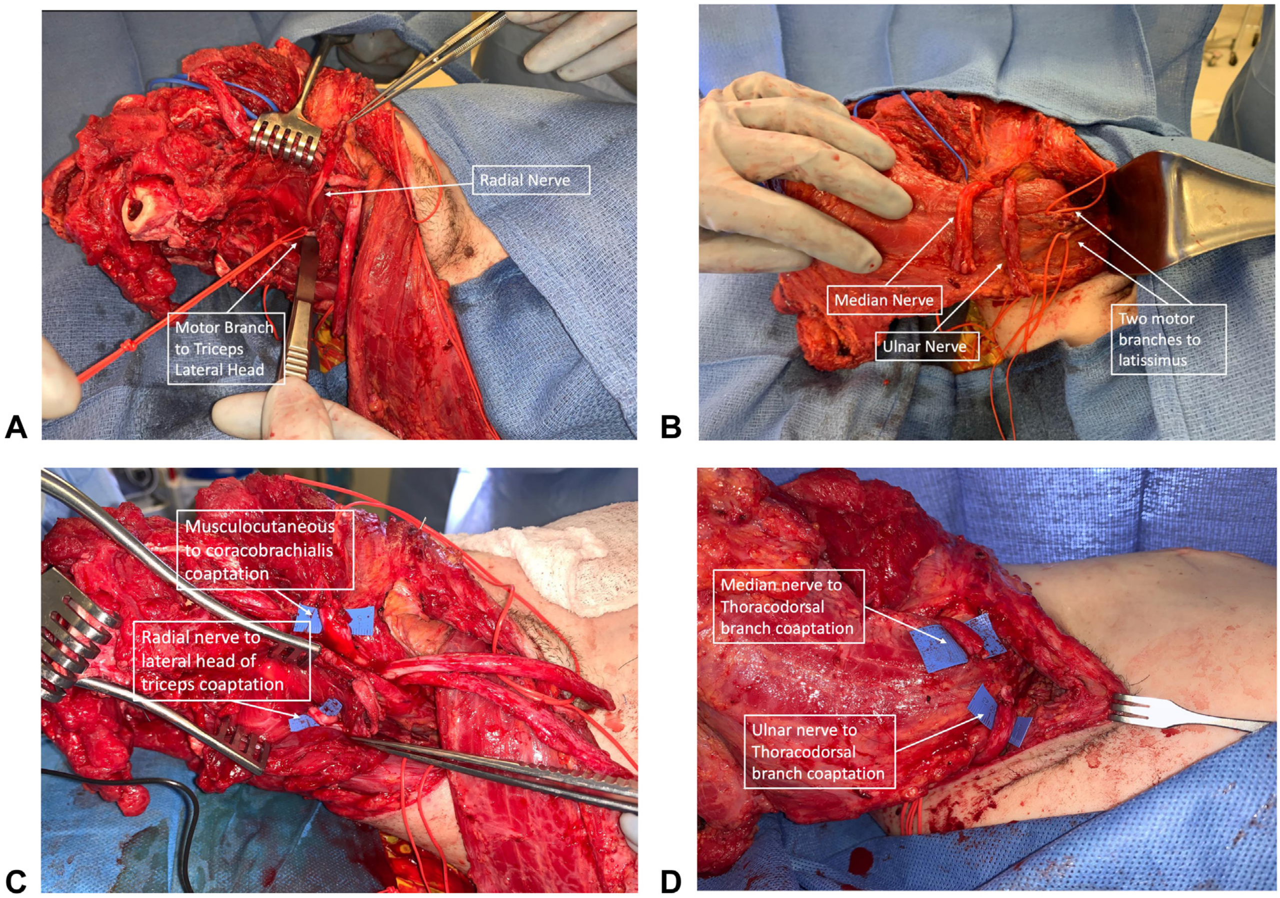

Figure 4. **A** Lateral head of an isolated triceps motor branch with adjacent continuation of the radial nerve retracted in forceps. **B** The latissimus flap draped over the wound, with red vessel loops around the 2 thoracodorsal motor branches. The median and ulnar nerves draped across the flap. **C** The musculocutaneous-to-coracobrachialis transfer (upper) and radial-to-lateral head of triceps (lower) coaptations. **D** The median and ulnar nerves coapted to the thoracodorsal motor branches of the latissimus flap.

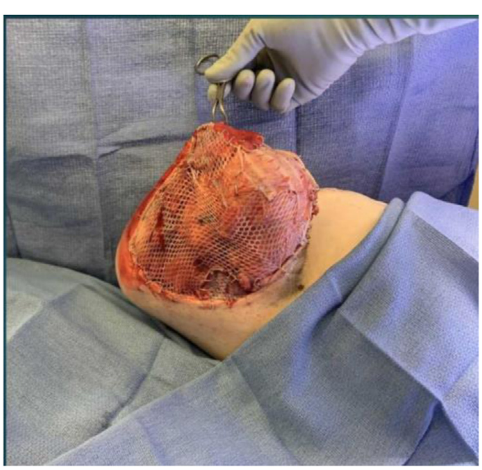

Figure 5. Wound appearance after latissimus flap inset and meshed split-thickness skin graft.

motor branch to the lateral head of the triceps, and her median and ulnar nerves to the 2 motor branches of the latissimus dorsi (Fig. 4). The flap was inset over a closed-suction drain, and a split-thickness skin graft was applied over the muscle flap (Fig. 5). An elastic bandage wrap was applied holding the arm to the torso to prevent abduction and tension on the coaptations. This was removed on postoperative day 3.

By 3 months after the surgery, the patient had a well-healed skin graft and flap (Fig. 6). She had regained excellent range of motion of the shoulder joint in flexion, abduction, and extension. Her phantom and neuropathic pain reduced markedly at approximately 4 months after the surgery; however, she continued to have a painful lump in the axilla which raised concern for a neuroma. One year after the surgery, this was explored because of persistent symptoms, and it was found that one of the coaptations had become disrupted (from the median nerve to the latissimus branch). The neuroma was excised and the coaptation revised. However, unfortunately, the patient was lost to follow-up thereafter. We believe that this disruption occurred in the early postoperative period because the patient later reported that she had difficulty keeping the shoulder joint adducted, likely because of unopposed deltoid activation, which subsequently improved. In the future, we would recommend considering more aggressive measures, such as strapping the limb to the torso for 3–4 weeks to avoid this complication.

Prosthetic planning and virtual reality training with prostheses were initiated within a month of the original operation. The patient regularly engaged in virtual rehabilitation sessions and reported that she was able to control the virtual prosthetic hand intuitively after several sessions.

Figure 6. A postoperative photograph taken at 5 months showing a healed skin graft and latissimus flap.

References

1. Hijjawi JB, Kuiken TA, Lipschutz RD, Miller LA, Stubblefield KA, Dumanian GA. Improved myoelectric prosthesis control accomplished using multiple nerve transfers. *Plast Reconstr Surg*. 2006;118(7):1573–1578.
2. O'Shaughnessy KD, Dumanian GA, Lipschutz RD, Miller LA, Stubblefield K, Kuiken TA. Targeted reinnervation to improve prosthesis control in transhumeral amputees: a report of three cases. *J Bone Joint Surg Am*. 2008;90(2):393–400.
3. Valerio IL, Dumanian GA, Jordan SW, et al. Preemptive treatment of phantom and residual limb pain with targeted muscle reinnervation at the time of major limb amputation. *J Am Coll Surg*. 2019;228(3):217–226.
4. Souza JM, Cheesborough JE, Ko JH, Cho MS, Kuiken TA, Dumanian GA. Targeted muscle reinnervation: a novel approach to postamputation neuroma pain. *Clin Orthop Relat Res*. 2014;472(10):2984–2990.
5. Valerio IL, Larsen M, Eberlin KR. Application of spare parts in combination with targeted muscle reinnervation surgery. *Plast Reconstr Surg*. 2021;147(2):279e–283e.
6. Bakri K, Mardini S, Evans KK, Carlsen BT, Arnold PG. Workhorse flaps in chest wall reconstruction: the pectoralis major, latissimus dorsi, and rectus abdominis flaps. *Semin Plast Surg*. 2011;25(1):43–54.
7. Miller LA, Stubblefield KA, Lipschutz RD, et al. Surgical and functional outcomes of targeted muscle reinnervation. In: Kuiken TA, Schultz Feuser AE, Barlow AK, eds. *Targeted Muscle Reinnervation: A Neural Interface for Artificial Limbs*. CRC Press; 2013:149–164.
8. Lu D, Myers H, Bruscino-Raiola F. Pedicled serratus anterior flap as an alternative muscle target for targeted muscle reinnervation in transhumeral amputees. *J Hand Surg Am*. 2019;44(11):997.e1–997.e6.
9. Chang BL, Mondshine J, Attinger CE, Kleiber GM. Targeted muscle reinnervation improves pain and ambulation outcomes in highly comorbid amputees. *Plast Reconstr Surg*. 2021;148(2):376–386.
10. Kuiken TA, Barlow AK, Hargrove L, Dumanian GA. Targeted muscle reinnervation for the upper and lower extremity. *Tech Orthop*. 2017;32(2):109–116.