Current Concepts in Upper-Extremity Amputation

Sarah N. Pierrie, MD,* R. Glenn Gaston, MD,*† Bryan J. Loeffler, MD*†

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Learning Objectives

Upon completion of this CME activity, the learner should achieve an understanding of:

- Optimum length of election for amputation stumps of the major upper extremity bones
- Methods available to lengthen amputation stumps for better prosthetic fitting
- The principles and goals of targeted muscle reinnervation to create novel myoelectric signaling
- Advances in prosthetics

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Advances in motor vehicle safety, trauma care, combat body armor, and cancer treatment have enhanced the life expectancy and functional expectations of patients with upper-extremity amputations. Upper-extremity surgeons have multiple surgical options to optimize the potential of emerging prosthetic technologies for this diverse patient group. Targeted muscle reinnervation is an evolving technique that improves control of myoelectric prostheses and can prevent or treat symptomatic neuromas. This review addresses current strategies for the care of patients with amputations proximal to the wrist with an emphasis on recent advancements in surgical techniques and prostheses. *(J Hand Surg Am. 2018;43(7):657−667. Copyright © 2018 by the American Society for Surgery of the Hand. All rights reserved.)*

*From the *Department of Orthopaedic Surgery, Atrium Health; and the †OrthoCarolina Reconstructive Center for Lost Limbs, Charlotte, NC.*

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Corresponding author: R. Glenn Gaston, MD, OrthoCarolina Hand and Wrist Center, 1915 Randolph Road, Charlotte, NC 28207; e-mail: Glenn.Gaston@orthocarolina.com.

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INTRODUCTION

Major upper-extremity amputees account for only 8% of the 1.5 million individuals living with limb loss.[1] Upper-extremity amputation is an accepted treatment option for acute trauma or sequelae of traumatic injuries, chronic infection, bone or soft tissue tumors, certain brachial plexus injuries, and complex regional pain syndrome. Regardless of the underlying diagnosis, emphasis is placed on definitively treating the underlying condition, achieving a stable, functional extremity, and minimizing painful sequelae. Patients and providers benefit from a multidisciplinary team consisting of experienced upper-extremity surgeons, skilled prosthetists and/or orthotists, physiatrists, pain management physicians, and therapists.

SURGICAL RECONSTRUCTION

Preoperative considerations

Upper-extremity amputation should be considered a reconstructive procedure rather than an ablative procedure, taking into account a number of considerations of the host and limb (Table 1). Definitive procedures require clean, well-vascularized wound beds with adequate soft tissue coverage; complex wounds or active infection necessitate a staged approach. When amputations are performed (semi) electively, preoperative nutritional status should be optimized and patients should be evaluated by a prosthetist before surgery when possible.

Primary amputation

The creation of a stable osseous and soft tissue envelope that will maximize function of a prosthesis and minimize pain is the principal goal of primary amputation. In contrast to weight-bearing and mobilization considerations in the lower extremity, the ability to interact with the environment is underscored for the upper extremity. Prosthetic fit and function between amputation levels have been assessed by few biomechanical studies or standardized trials, but clinical experience has highlighted several important considerations.[2–4]

Intuitively, the ability to optimally interact with the environment is positively associated with preservation of limb length. The most proximal amputations (shoulder disarticulation or forequarter amputation) require cumbersome prostheses, which necessitate considerable energy expenditure. In our clinical practice, we make every effort to salvage the elbow and shoulder joints when feasible to enhance post-amputation function. In short amputations through long bones (as with high transradial or high transhumeral amputations), the function of the adjacent (proximal) joint may be obviated. To enable prosthetic suspension, a minimum of 5 cm of bone distal to a joint is needed to preserve the function of that joint in a prosthesis.[5] While a distal third forearm amputation leaves the origin and insertion of the pronator teres and supinator intact, patients rarely exhibit functional rotation of the residual limb.

Successful lengthening of short upper extremity residual limbs to improve prosthetic function has been described in both children and adults[6,7,a] (Figs. 1, 2). Microsurgical free-tissue transfer (with free flaps or fillet flaps from unreplantable limbs) can be employed to preserve residual limb length, preserve joint function, and provide adequate soft tissue coverage.[5,8] These procedures should not be undertaken lightly, however, given the reported 38% complication rate. Complications such as flap necrosis, vascular impairment, and delayed union of a vascularized fibula flap have been described.[5] Free tissue transfer may also prolong soft tissue healing or change the residual limb shape, delaying prosthetic fitting and prolonging rehabilitation. Personal preferences and patient characteristics (particularly age, occupation, and medical comorbidities) should be considered before free tissue transfer using a shared decision-making strategy.

In contrast, disarticulations have their own drawbacks and benefits. Disarticulations create long residual limbs that adapt poorly to many modern prostheses and often require soft tissue augmentation or support (myodesis or myoplasty) to cover bony prominences and ensure a comfortable prosthetic fit. An important advantage of disarticulations, however, is improved suspension and rotational control of the prosthesis as a result of preserved distal condyles and intact muscle units. Diaphyseal humeral shortening, performed in conjunction with elbow disarticulation, can improve prosthetic fit and rotational control while preserving adequate space for the prosthesis.[9,10]

TABLE 1. Factors Influencing the Decision to Proceed With Amputation and the Level of Amputation

Host factors
Concomitant injuries or illnesses
Preoperative functional status
Expectations
Limb factors
Level of injury or disease
Type of injury or disease
Presence of contamination or infection
Soft tissue coverage
Vascular supply
Neurologic status

Much the same way that a long-arm cast is difficult to keep on a child without a good supracondylar mold, prosthetic suspension can be particularly challenging in short residual limbs without a distal condylar flare. The benefit of retained humeral condyles can be simulated in long transhumeral amputees with an angulation osteotomy (humeral flexion osteotomy).[11,12] In 1974, Marquardt and Neff[11] described 3 osteotomy techniques and outlined the advantages of these procedures, including improved functional shoulder rotation, augmented soft tissue coverage of the distal limb (through distal skin traction), and improved prosthetic stability. Neusel and colleagues observed that more than one-third of angulation osteotomies in skeletally immature patients straightened over time; however, loss of angulation occurred in none of the adult patients undergoing the procedure.[12] An angulation osteotomy may obviate the need for a shoulder harness to suspend a myoelectric arm and markedly improves rotational control of the arm (Fig. 3).

There are numerous other strategies for optimizing limb length and orientation, upper-extremity motion, and prosthetic fit (Table 2). To optimize limb length, soft tissue envelope, and functional outcomes, it is important that surgeons understand the technical specifications and requirements for current prostheses.[4] Regardless of amputation level, secondary procedures to address sequelae (wound complications, infection, bony overgrowth, elbow flexion contracture, or painful neuromas) are common.

Targeted muscle reinnervation

Targeted muscle reinnervation (TMR), the transfer of functioning nerves that have lost their operational target to intact proximal muscles that serve as biologic amplifiers,[13] has gained considerable momentum in tandem with advances in myoelectric prostheses. The "switch innervation" of a functioning nerve to a new muscle target creates a novel electric signal detectable by the myoelectric prosthesis and confers additional degrees of active motion. Several case reports and small series have described positive outcomes with TMR, but further work is needed to maximize the potential of this novel therapy.[14–19]

Targeted muscle reinnervation can enhance prosthetic function in patients with existing amputations, maximize the potential for prosthetic use in managing acute amputations,[15] and prevent or treat painful neuromas.[20,21] Acute TMR avoids a secondary surgery, diminishes the risk of painful neuromas, and accelerates achievement of maximal control and function of myoelectric prostheses. Targeted muscle reinnervation is contraindicated in patients with ipsilateral brachial plexopathy, major medical comorbidities, or anticipated prosthetic noncompliance in the absence of painful neuromas.

Although general TMR techniques have been described, the pattern of nerve transfer is nonprescriptive and depends on the amputation level (glenohumeral, transhumeral, and transradial amputations), length and function of local peripheral (donor) nerves, and presence or function of remaining muscle targets.[13,22,23] In transhumeral amputees, only the biceps and triceps muscles are able to create meaningful signals for a myoelectric prosthesis. Separating the heads of the biceps and triceps, recruiting the brachialis, and "switch innervating" some of these muscles with the terminal radial, median, and ulnar nerves with TMR increases the number of signals available for use with a modern myoelectric prosthesis. For example, the medial biceps head can be denervated by cutting its musculocutaneous nerve motor branches and then reinnervated by coapting the median nerve to these motor branches, allowing the medial head of the biceps to contract intuitively when grasp is desired. The preserved lateral biceps head, still innervated by the musculocutaneous nerve, contracts normally when elbow flexion is desired. Similarly, one triceps head can be "switch innervated" with the distal radial nerve to control digital extension of a myoelectric prosthesis. The remaining heads of the triceps, innervated by radial nerve motor branches, are preserved for elbow extension. When available, we typically reinnervate the brachialis with the ulnar nerve.

Surgical technique

Targeted muscle reinnervation begins with identifying and mobilizing donor nerves. While preserving maximal length, end neuromas are excised and

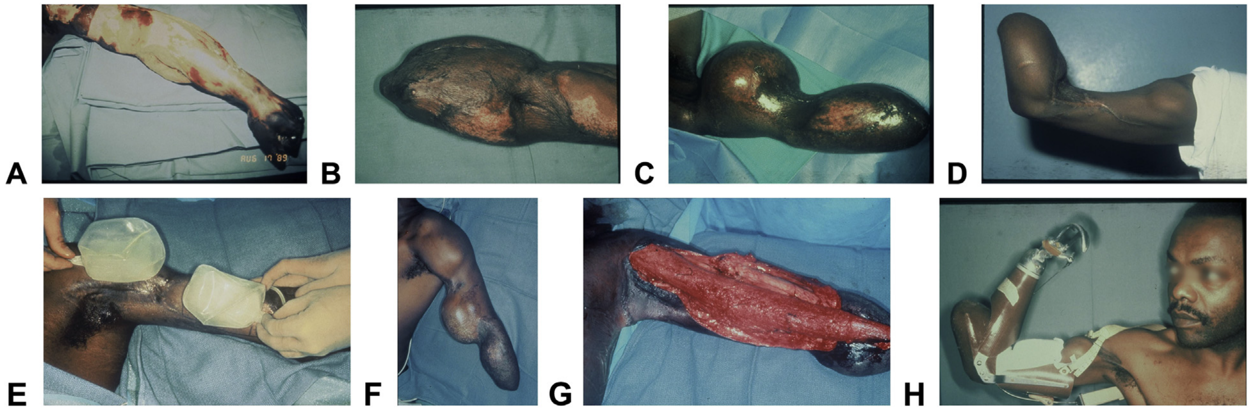

FIGURE 1: **A** The patient sustained bilateral high-tension electrocution injuries. **B** He underwent bilateral proximal forearm amputations. The surgeon was forward-thinking and retained the elbow joint even though the distal biceps was severely damaged and skin grafting was necessary directly over the ulna and radius bone stumps. **C, D** Skin expansion enabled pliable, thin, and durable soft tissue coverage over the distal amputation stump on each side. **E, F** In yet another stage, tissue expanders were placed in the upper arm. **G** In this way, sufficient space was created to transfer a functional latissimus dorsi pedicle muscle transfer. **H** The patient became a successful prosthesis wearer. (Clinical case courtesy of David Netscher, MD.)

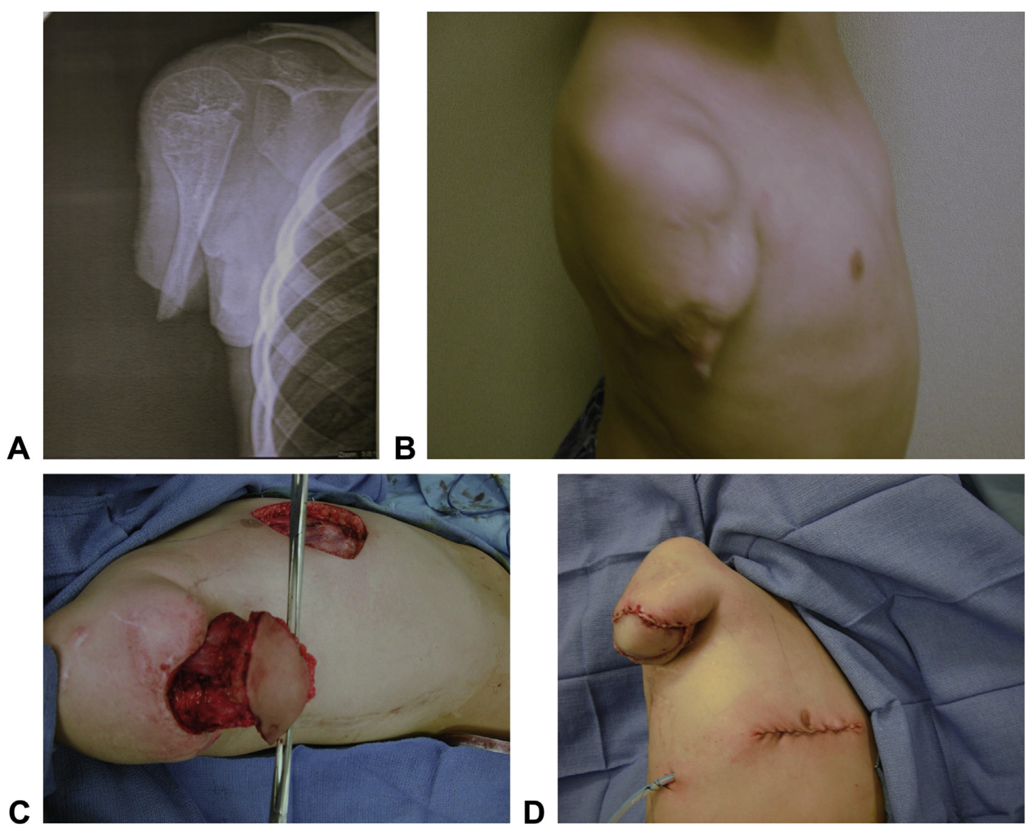

FIGURE 2: **A** A teenage boy sustained a traumatic high-transhumeral amputation. Bone was lengthened by distraction. **B** The distal end of the bone was in danger of becoming exposed through the skin. **C, D** The pectoralis major musculocutaneous pedicle flap provided soft tissue coverage to the distal amputation stump. (Clinical case courtesy of David Netscher, MD.)

fascicles are trimmed until axoplasmic sprouting of nerve fascicles is noted. Target muscles are then identified and the separate heads of the biceps and triceps are isolated. Next, the target muscles' native motor nerves are identified and transected roughly 1 cm proximal to the neuromuscular junction. The stump of the target muscle's native motor branch is buried in muscle away from its original target to

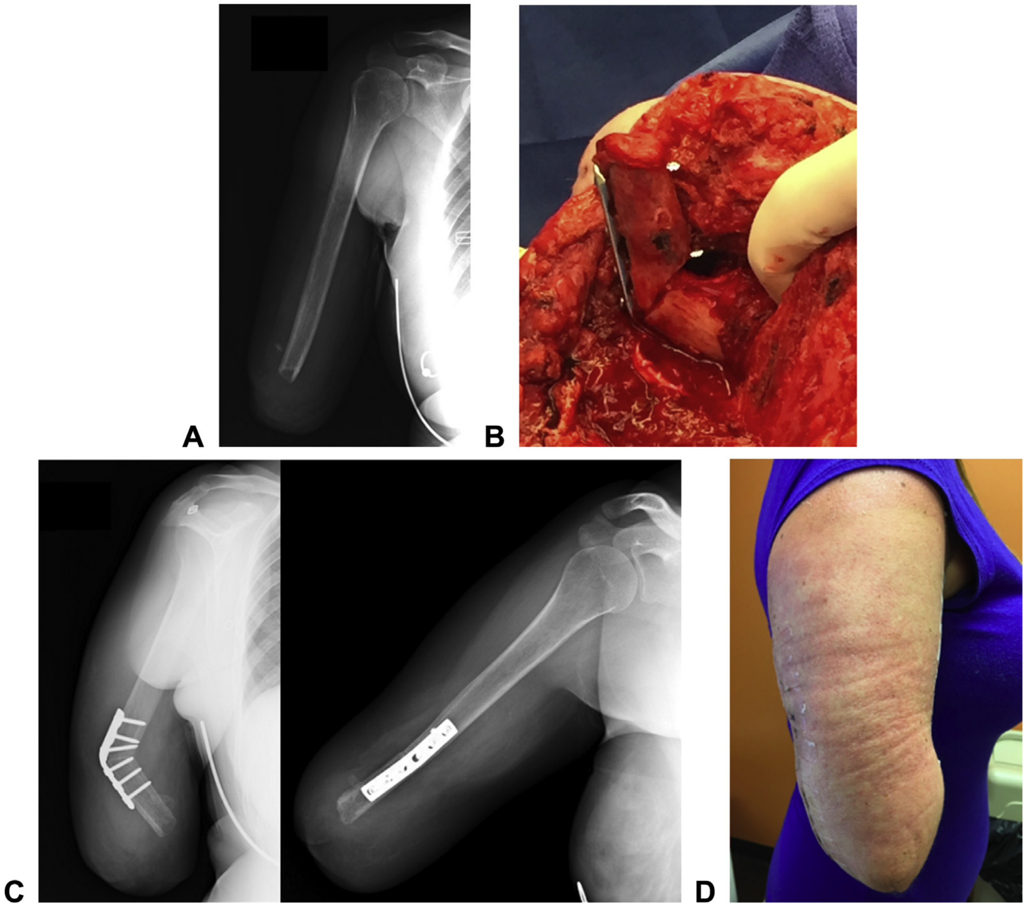

FIGURE 3: Humeral flexion osteotomy to improve prosthetic suspension and functional upper-extremity motion. **A** Radiograph of long-transhumeral amputation. **B** Intraoperative photo of a humeral flexion osteotomy performed through a posterior approach in the same setting as targeted muscle reinnervation. **C** Postoperative radiograph after humeral flexion osteotomy. **D** Clinical photo of the residual limb after humeral flexion osteotomy.

TABLE 2. Strategies for Optimizing Limb Length and Orientation, Prosthetic Suspension, and Prosthetic Rotational Control

Limb-lengthening procedures	Lengthens a short residual limb to improve prosthetic suspension or fit
Microvascular free tissue transfer (eg, free flap, fillet flap, vascularized free fibula graft)	Improves soft tissue coverage Vascularized bone transfer: may lengthen a short residual limb
Shortening osteotomy	Shortens a disarticulation or long residual limb Improves prosthetic suspension and rotational control when condyles are retained Can improve soft tissue coverage May reduce the risk of heterotopic ossification when performed away from the zone of injury
Humeral flexion osteotomy	Simulates a condylar structure to improve prosthetic suspension Improves functional shoulder motion May improve distal soft tissue coverage May shorten a disarticulation or long residual limb

avoid the native nerve reinnervating the targeted muscle.

The donor nerve is coapted to the target nerve through a tension-free end-to-end repair, then augmented with an epineurium-to-epimysium repair (Fig. 4). This is particularly advantageous if there is a mismatch in the caliber of the donor and recipient nerves.[13] If a native motor stump is not available

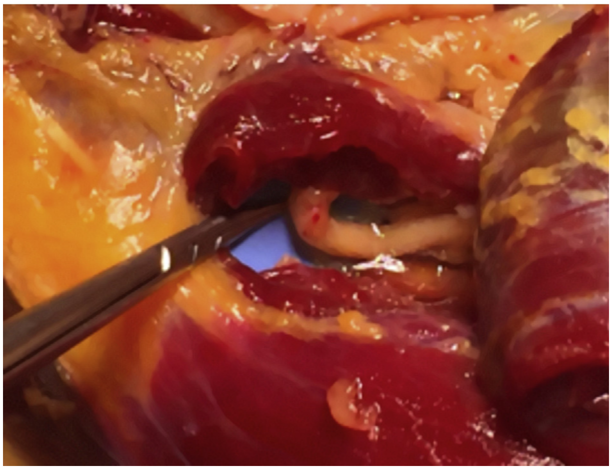

FIGURE 4: An epineurium-to-epimysium repair can be used to augment a direct nerve-to-nerve transfer during TMR surgery.

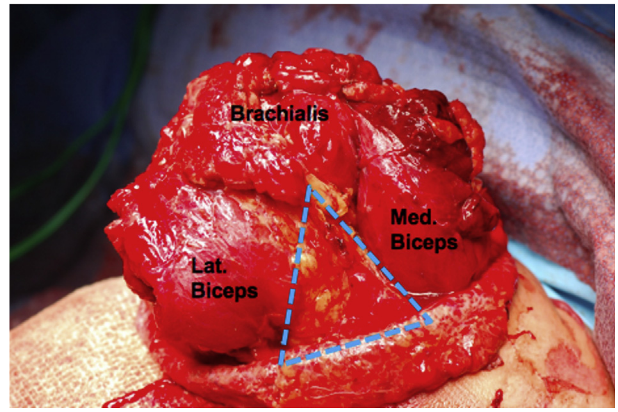

FIGURE 5: An adipofascial flap (dashed triangle) separates the medial and lateral biceps (Med. Biceps and Lat. Biceps, respectively) after switch innervation of the median nerve to the medial biceps.

owing to damage or avulsion, the donor nerve end can be sutured directly into an acutely injured denervated muscle.

One challenge with independent signal detection is overlapping myoelectric signals produced by muscles with different functions in close proximity to one another, termed muscle cross-talk. For example, the long and short heads of the biceps are next to each other, but after nerve transfer they have separate innervations. Surface electrodes may struggle to distinguish the overlapping myoelectric signals produced by the 2 individual muscles. Cross-talk can be minimized by placing pedicled adipofascial flaps between 2 muscles, effectively insulating myoelectric signals in their respective compartments (Fig. 5). Before closure, subcutaneous adipose tissue should be focally thinned to reduce the distance and interference between the skin and targeted muscles.

Targeted muscle reinnervation for management of painful neuromas

Approximately one-quarter of upper-extremity amputees struggle with painful neuromas, which impede postoperative rehabilitation and long-term prosthetic use.[24,25] Major peripheral nerves are often managed by traction neurectomy at the time of primary amputation. Unfortunately, painful neuromas may develop as a result of disorganized fibroblast and Schwann cell proliferation. Several prevention and treatment techniques have been described, including burial of the nerve ending in muscle or bone and, more recently, the use of TMR. With TMR, end-to-end coaptation of lacerated nerves to target muscle motor branches encourages organized nerve healing, as demonstrated in animal models of neuroma formation after TMR.[26]

Souza and colleagues[20] reported that 14 of 15 patients with preexisting neuroma pain experienced the complete resolution of symptoms after TMR for improved prosthetic control, whereas none of the 26 total patients included in the study group developed postoperative neuroma pain. Pet and colleagues[21] treated 23 patients with upper-extremity amputations and symptomatic neuromas with TMR and reported an 87% decrease in neuroma pain. Likewise, in 12 amputees treated with TMR for neuroma prevention at the time of primary amputation, 92% were pain-free at a mean of 22 months after surgery. No neuromas have been reported after TMR surgery.

Restoring sensation

Establishing bidirectional control (motor function and tactile feedback) of the prosthesis and residual limb represents the crux of functional prosthesis use. Conventional prostheses do not reproduce pain, sensation, or proprioception; thus, prosthetic users rely on sensation from the residual limb, in addition to visual and environmental cues. Restoring sensation is important for integrating environmental stimuli, providing intuitive prosthetic function, and integrating the prosthesis into patient self-perception.[27]

Analogous to TMR, targeted sensory reinnervation creates new neural pathways through the transfer of transected peripheral sensory nerves to denervated skin on the upper arm or chest wall. Sensors on the prosthesis can transmit stimuli to the corresponding reinnervated skin to produce tactile feedback. For example, sensory fibers of the transected median nerve are used to reinnervate a more proximal, intact cutaneous nerve. Force applied to sensors on the volar aspect of the prosthetic thumb, index, and middle fingers can be detected and transmitted to a stimulator over the now median innervated skin. The stimulator applies force to the reinnervated skin, creating an afferent signal to the median nerve, sensed as varying degrees of light touch, pain, temperature, and proprioception,[28,29] although these sensory signals may degrade over time.[30] Early studies of cortical pathways demonstrate neuroplasticity associated with sensory reinnervation.[31]

Several nascent engineering and clinical studies have demonstrated that implantable haptic technology (epineural, interneural, and intraneural electrodes) can provide touch, pressure, shear, and even temperature sensation.[32,b]

Electrode cuffs or grids placed around, on, or within peripheral sensory nerves can provide both stimulation and real-time feedback. In the lab, 2 prosthetic users with implanted myoelectrodes could perceive diverse sensory stimuli in the appropriate peripheral nerve distribution under experimental conditions.[33] Kim and Colgate[34] showed that these devices could improve grip force control in early trials.

The Defense Advanced Research Program's Hand Proprioception and Touch Interfaces program also seeks to create prostheses with sensory feedback. In this strategy, force sensors are applied to the prosthetic fingertips, generating signals that are transmitted to native residual nerves through surgically implanted nerve cuffs (Fig. 6). Early unpublished results indicate that the use of this technology improves dexterity and fine motor control of the myoelectric prosthesis without the need for visual feedback.

ADVANCES IN PROSTHETICS

The complicated movements, dexterity, and functional capacity of the human hand have not yet been replicated with prostheses. Despite recent advances in prosthetic design, the functional gap between the natural hand and prosthetic options remains greater than the ability of prostheses to mirror the weight-bearing functional capacity of the lower limbs. Prosthetic users often cite limited dexterity as the primary reason for abandoning the prosthesis. There are advantages and disadvantages between classes of upper-extremity prostheses (Table 3).

Pattern recognition myoelectric prostheses

Conventional myoelectric prostheses (so-called direct-control prostheses) translate EMG signals from an agonist—antagonist muscle pair into actions in a single plane. For example, EMG signals from the biceps and triceps in a transhumeral amputee allow elbow flexion and extension, respectively. Direct-control systems interpret and act upon the amplitude of EMG signals obtained from their muscle targets. Although these systems have evolved to allow a second degree of freedom (eg, hand open and closed) after a mode switch signaled by either a mechanical switch or a specific muscle co-contraction, their function is usually limited to 2 degrees of freedom and users report that the obligate mode switch is not intuitive.

In contrast, myoelectric prostheses equipped with pattern recognition technology initiate limb movement in response to a reproducible pattern of EMG signals produced by muscle contraction.[35] Early work by Hudgins' group[35] revealed that elbow and upper-arm motion in 2 planes (flexion-extension and rotation) conferred reproducible EMG signal patterns among transhumeral amputees. Advances in sensor technology and computer software have created systems capable of sensing subtle user-specific EMG patterns and summarily retraining the software to accommodate stump-volume fluctuation, the position of the residual limb within the socket, and socket fit. Whereas TMR maximizes degrees of freedom in both types of myoelectric prosthesis, it is particularly advantageous in association with pattern recognition prostheses.[16—18]

Physiological factors (such as muscle fatigue, compromised soft tissue envelope, and sweating), a change in limb position, and motion artifact may degrade the number or quality of EMG signals interpreted by surface electrodes. Technological advances in implantable intramuscular or intraneural EMG sensors may improve the number and quality of myoelectric signals available for interpretation.[33,36] Pattern recognition remains limited to sequential control; thus, tasks requiring complex movements must be performed in stepwise fashion by individual simple movements. For example, opening a door requires shoulder flexion and elbow extension to reach for the door, followed by forearm pronation and digital extension to touch the doorknob. Grasping and turning the doorknob requires digital flexion and forearm supination. Pattern recognition enables each of these individual simple movements to be performed sequentially.[37] Emerging software may have predictive and adaptive capabilities, closing the gap between current technology and intuitive prosthetic function.

Osseointegration

Osseointegrated (OI) implants have allowed bone anchorage of external prostheses among transhumeral

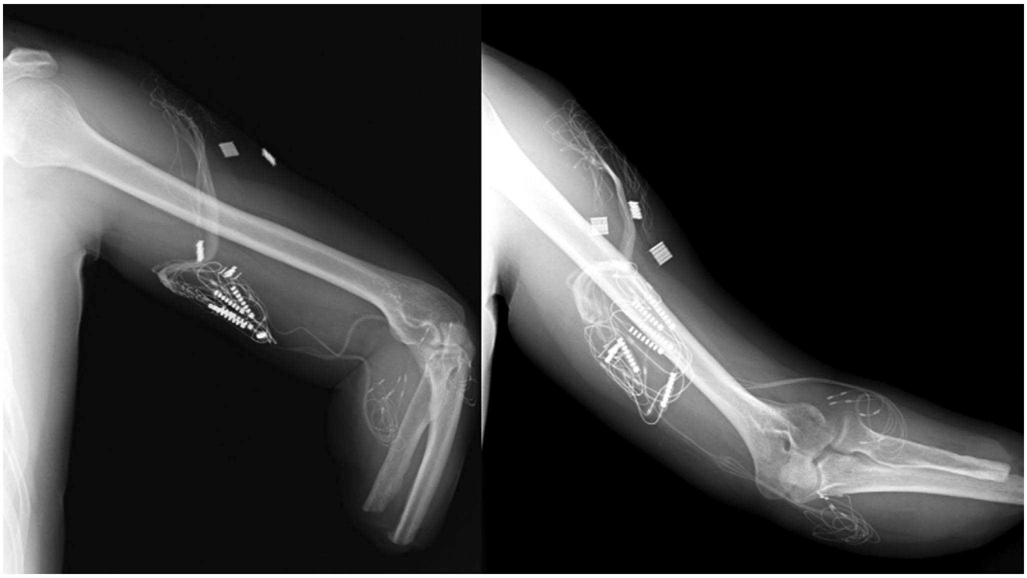

FIGURE 6: Neurocutaneous electrodes were surgically implanted around the median and ulnar nerves. Force sensors applied to prosthetic fingertips generate signals that are transmitted to native residual nerves through the surgically implanted nerve cuffs. The external circuitry connecting the prosthesis to the electrodes exits inferior to the deltoid.

TABLE 3. Classes of Upper-Extremity Prostheses

Type	Mechanism	Advantage	Disadvantage
Cosmetic	Socket attaches to residual limb	Most cosmetic	No mechanical function is conferred by prosthesis
Body-powered	Shoulder motion is captured with a harness and transferred through a cable to operate a distal joint	Inexpensive Highly functional for basic tasks	Only one joint can be operated at a time Heavy and unwieldy; can be physically demanding
Myoelectric	Electrical signals produced by muscle contraction are captured by surface electrodes and used to operate a motorized arm	Provides a strong grip TMR: increases potential degrees of freedom	Only one function can be performed at a time Heavy Control is not intuitive; may require mode switch to increase degrees of freedom Signal quality is adversely affected by poor socket fit and cross-talk (EMG noise from adjacent muscles that dilutes signal quality)

amputees in Europe for 2 decades, but they are not currently approved by the United States Food and Drug Administration.[38] An intramedullary fixture and transcutaneous titanium abutment are surgically introduced to the residual limb in staged fashion. Because these prostheses attach directly to the end-bearing OI implant, osseointegration eliminates many of the problems associated with traditional socket prostheses, including pain and soft tissue injury related to sweating, chafing, and poor prosthetic fit. It also confers a mechanical advantage by improving prosthetic suspension and rotational control relative to traditional socket prostheses and provides limited osseoperception. Potential for infectious complications and longevity remain major arguments against transcutaneous implants, however. Although colonization at the implant—skin interface is common, it does not affect prosthesis use in most patients.[39] In a cohort of 18 patients with transhumeral amputations, Tsikandylakis and colleagues[40] reported 80% cumulative implant survival at 5 years after implantation; however, there were 43 adverse events, including superficial (15 events in 5 patients) and deep (1 event) infections, skin reactions at the skin penetration site (8 patients), incomplete fractures during fixture placement (8 patients), and phantom limb pain (3 patients). Of the 3 patients who experienced implant failure, 2 were revised for loosening; both had positive intraoperative cultures and were treated with staged revision surgery. Taken together, these data suggest that OI prostheses may be an acceptable alternative to conventional socket prostheses in select patients.

More recently, OI condylar implants were introduced to address restricted shoulder motion, minimize skin irritation, and improve prosthetic fit while minimizing the infection risk associated with OI implants. Witso and colleagues[41] first devised a cemented T-shaped subcutaneous implant and reported successful integration and use in 2 of 3 patients with transhumeral amputations. To address some of the issues associated with its earlier counterpart, Salminger et al[42] created a butterfly-shaped titanium subcutaneous implant-supported attachment, the SISA. This condylar implant can be grasped by a customized, 3-dimensionally printed socket designed to improve ease of prosthetic application and distribute pressure more uniformly for a comfortable fit. Although promising clinical results have been reported, including minimal restriction in shoulder motion, 9.5 hours average wearing time, and no soft tissue wounds in 2 transhumeral amputees, the authors caution that subcutaneous implants should be reserved for patients with adequate healthy soft tissue at the end of the residual limb. In patients with adequate residual limb length but no condylar structures in whom OI is not an option, humeral flexion osteotomy can improve functional shoulder motion and prosthetic fit in transhumeral amputees.[11,12]

A potential benefit of OI prostheses is improved detection of sensory signals from the local environment, a process known as osseoperception, which relies on unmyelinated nerve fibers in bone and sensory fibers in adjacent soft tissues to transmit sensory information to the central nervous system. Functional magnetic resonance imaging has shown activation of the somatosensory cortex in response to stimulation of osseointegrated prostheses.[43] In a recent study of 34 patients with transfemoral amputations, Haggstrom et al[44] reported that patients with OI prostheses had improved ability to detect vibratory stimuli compared to their peers with suspended prostheses. Furthermore, the detection threshold for certain frequencies decreased over time compared with preoperative values, which raised the question of whether osseoperception may be a plastic process that can improve over time.

CHALLENGES AND FUTURE DIRECTIONS

Targeted muscle reinnervation surgery has dramatically improved control of myoelectric prostheses and simultaneously addressed the challenge of painful neuromas in patients with upper-extremity amputations. Further technical modifications coupled with technological advances will likely result in more sophisticated prosthetic control and function. Investigators seek increased degrees of freedom through a single joint, including wrist flexion and extension and radioulnar deviation; coordinated control of multiple joints; co-completion of simultaneous movements, known as muscle synergy; and improved hand function through pinch, grasp, opposition, and ulnar grip.[15] These advances require concurrent innovation in both the surgical and prosthetic realms. Surgeons continue to investigate novel TMR targets that increase the number and quality of myoelectric signals available to power a prosthesis. Corresponding advances in prosthetics technology such as implanted intramuscular or intraneural myoelectric sensors (as opposed to surface electrodes) offer a robust, reliable means of obtaining independent electromyographic signals from muscles in close proximity.[33,36] Enhanced myoelectric prostheses ultimately will have additional degrees of freedom with independent and intuitive prosthetic control, in part by increasing the number of available muscle targets. In addition, patients with severe soft tissue injury such as scars and burns may have difficulty powering a myoelectric prosthesis using current sensor technology. Future work is needed to improve sensor density and precision and to identify strategies that minimize cross-talk.

Major upper-extremity amputation has a profound effect on an individual's productivity and ability to interact meaningfully with his or her environment. Although numerous strategies exist to optimize limb length, orientation, and motion, complications and secondary procedures are common. Targeted muscle reinnervation is an emerging technique that improves myoelectric prosthesis use while preventing and treating painful neuromas. Targeted sensory innervation and prosthetic innovations such as osseointegration are promising developments that may improve prosthetic user comfort and function. Despite important advances in surgical techniques and prostheses, maximizing prosthetic function and use remains an exciting objective for upper-extremity surgeons, prosthetists, and patients.

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EDITOR'S SUGGESTIONS FOR MORE INFORMATION

a. Distraction lengthening for partial traumatic thumb amputation [Video A]. Stone J, Nydick J. Presented at the American Society for Surgery of the Hand annual meeting, Video Theater, September 7 through 9, 2017, San Francisco, CA. Also available on Hand-e: http://www.assh.org/hand-e.

b. Dexterous hand control through fascicular targeting (HAPTIX-DEFT) [Video B]. Cheng J, Keefer E. Presented at the American Society for Surgery of the Hand annual meeting, September 7 through 9, 2017, San Francisco, CA. Also available on Hand-e: http://www.assh.org/hand-e.

c. Limb amputations and prosthetics [Video C]. Lifchez SD. Presented at the Comprehensive Review in Hand Surgery Course, July 7 through 9, 2017, Chicago, IL. Also available on Hand-e: http://www.assh.org/hand-e.

d. Bilateral electric multi-articulating hands [Video D]. Atkins DJ. Presented at the American Society for Surgery of the Hand annual meeting, September 29 through October 1, 2016, Austin, TX. Also available on Hand-e: http://www.assh.org/hand-e.

JOURNAL CME QUESTIONS

Current Concepts in Upper-Extremity Amputation

1. What is the minimum length of residual bone in a major upper extremity amputation that is needed to preserve function of the adjacent proximal joint (elbow or shoulder) while wearing a prosthesis?

a. 3 cm
b. 5 cm
c. 7 cm
d. 9 cm
e. 12 cm

2. An angulation osteotomy for a patient with a transhumeral amputation is most likely to confer which of the following advantages?

a. Improved shoulder rotation and prosthetic suspension
b. Lengthens a short residual limb
c. Reduction of heterotopic ossification at the next proximal joint
d. Maintains a curvature and "hook" in the skeletally immature patient
e. Reduces neuroma sensitivity

3. Detection of myoelectric signals following targeted muscle reinnervation may be confounded by muscle "cross-talk." Which of the following statements best describes this phenomenon?

a. Disorganized nerve regeneration characterized by overgrowth of nerve fibers and Schwann cells
b. Electrode cuffs placed around or within peripheral sensory nerves
c. Overlapping myoelectric signals produced by muscles with different intended functions in close proximity to each other
d. The transfer of functioning nerves that have lost their operational target to intact proximal muscles may be difficult to reintegrate
e. Osseoperception detects additional sensory signals

4. What is the process by which unmyelinated nerve fibers in bone and sensory fibers in adjacent soft tissues transmit information to the central nervous system?

a. Advanced pattern recognition
b. Cross-talk
c. Osseo perception
d. Targeted sensory reinnervation
e. Haptic transmission

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