SURGICAL TECHNIQUE

Bionic Reconstruction for the Nonfunctional, Painful Hand: Optimizing Pre/Intra/Postoperative Treatment Using Elective Transradial Amputation and Targeted Muscle Reinnervation/ Regenerative Peripheral Nerve Interface

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The treatment of a nonfunctional, painful upper limb has historically been challenging. Bionic reconstruction, a technique that employs nerve and muscle transfers following an elective amputation to successfully facilitate prosthetic integration, overcomes the difficulties of previous treatment approaches. The biggest advantages conferred by a bionic reconstruction allow functional return of the injured limb in addition to mitigation of chronic pain. We describe a technique for elective transradial amputation using an all-fish-mouth technique that unites targeted muscle reinnervation with regenerative peripheral nerve interfaces for improved outcomes. In the implementation of the bionic reconstructive approach, a preoperative and postoperative multidisciplinary treatment approach is critical to optimize outcomes. We have outlined a novel comprehensive care protocol, including surgery, rehabilitation, prosthetics, and mental health treatment, to confer the success of the bionic technique. *(J Hand Surg Am. 2025;■(■):1.e1-e10. Copyright © 2025 by the American Society for Surgery of the Hand. All rights are reserved, including those for text and data mining, AI training, and similar technologies.)*

Key words Amputation, peripheral nerve surgery, prosthetics, regenerative peripheral nerve interfaces, targeted muscle reinnervation.

Online Exclusive

THE LOSS OF A FUNCTIONAL HAND has a tremendous negative impact on a patient's quality of life.[1,2] A dysfunctional and painful upper extremity is not only debilitating physically and psychologically but also impedes successful prosthetic integration. Historically, attempts to salvage a nonfunctional upper extremity have led to limited improvements in function and persistent chronic pain. When faced with this scenario, patients are often informed that there are no further

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treatment options and left solely with inadequate medical management of their pain.[1,2] Although limb salvage is attempted, and often initially preferred, there are potential limitations in the reconstructive outcome, further challenged by the potential need for multiple surgical procedures and a lengthy recovery process. Long-term management may lead to unsatisfactory results and leave patients with a nonfunctional upper extremity, with up to a 10% rate of amputation following attempted reconstruction.[3,4] Chronic pain and reduced functionality are reasons for which patients may request conversion from limb salvage to amputation, precipitating a need for a technique to alleviate pain while restoring function.[5] Bionic reconstruction, a reconstructive technique that employs nerve and muscle transfers following an elective amputation to successfully facilitate prosthetic integration and improve chronic pain, can be a viable solution in the face of failed limb salvage.

Advancements in surgical and prosthetic technology have enabled myoelectric prostheses to use existing electrical signaling from the patient's residual limb to power a device that is more adept at simulating natural limb function.[6] Targeted muscle reinnervation (TMR) reroutes severed nerves to target nerves or muscles in the residual limb, providing additional myosignals for prosthetic control. Although TMR had been initially applied to high-level amputees where the native musculature is insufficient for limb control, multiple recent studies demonstrate the benefits of TMR for all levels of upper-extremity amputation.[7] Regenerative peripheral nerve interface (RPNI) uses free muscle or dermal grafts as biological signal amplifiers for severed or damaged peripheral nerve endings. Regenerative peripheral nerve interfaces have demonstrated promise in decreasing the rate of neuroma formation, improving phantom pain while subsequently improving EMG signal conduction and amplification for improved use of myoelectric prosthetics.[8] Both TMR and RPNI have advanced the field of postamputation neuromuscular reconstruction, demonstrating success in improving neuroma control and reducing chronic nerve pain or phantom limb pain.[9]

Bionic reconstruction replaces a nonfunctional, painful upper extremity intractable to other solutions with a prosthetic that improves function while potentially eliminating associated pain. In this article, we present a novel technique for bionic reconstruction of the painful nonfunctional hand that incorporates both TMR and RPNI using a single transradial fish-mouth incision, combining two synergistic nerve interface strategies within a comprehensive surgical and multidisciplinary framework. Importantly, the success depends on both the proficiency of the surgical procedure and detailed preoperative and postoperative assessments using a multidisciplinary structure. A secondary aim of this article was to discuss the multidisciplinary protocol that has been developed to increase success with this technique.

INDICATIONS/CONTRAINDICATIONS

Bionic reconstruction is indicated in those patients with a painful, nonfunctional hand who have exhausted all other treatment modalities. Targeted muscle reinnervation and RPNI are performed for any patient who has undergone an amputation. Relative contraindication to TMR and RPNI includes severe proximal nerve damage, such as brachial plexus or spinal cord injury. Although higher-level nerve damage may be a relative contraindication to TMR or RPNI, it does not automatically exclude patients from bionic reconstruction, as a myoelectric prosthetic may improve overall functionality, even if improvement in pain is not a feasible goal (see patient 3).

PREOPERATIVE EVALUATION AND TECHNIQUE

Preoperative assessment and training are essential in the process of bionic reconstruction to maximize successful implementation of a prosthesis in the postamputation period. Myosite evaluation is the initial step to determine the future success, followed by surgical planning to offer additional myosites if needed.[10]

Preoperative rehabilitation protocol

Evaluation prior to elective trans-radial amputation includes assessing the range of motion of all joints proximal to the point of amputation. Patients are guided through exercises to develop strength and increase the range of motion. This training prepares patients to adequately support their future prosthetic.

The "prehab" implements a hybrid prosthetic, which serves a dual purpose—to demonstrate the prosthetic's utility before definitive amputation and to train patients in completing activities of daily living. Early exposure to the prosthetic allows patients to integrate it into daily life. Specific training exercises lead to increased independence postamputation (Video S1, available online on the *Journal*'s website at www.jhandsurg.org). Over a typical 3-month preoperative

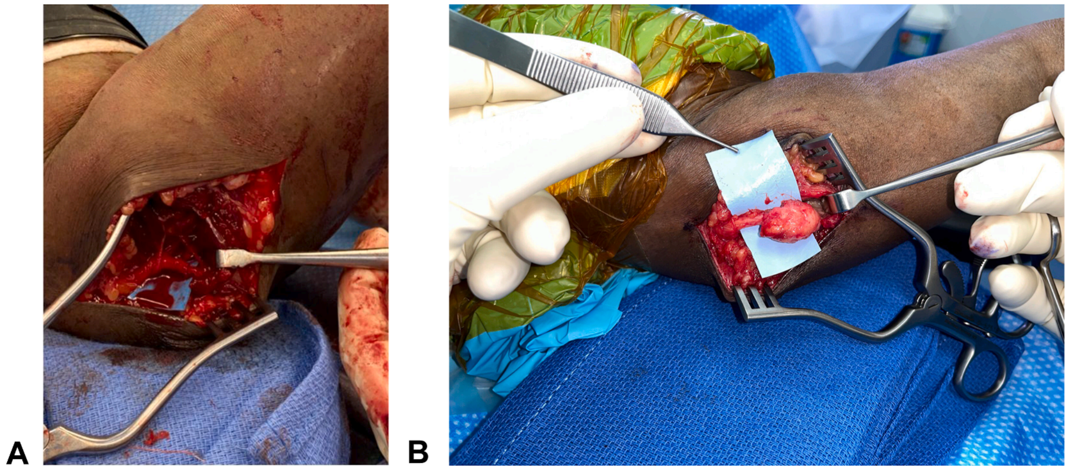

FIGURE 1: **A** Transfer of the ulnar nerve to the FCU branch of the ulnar nerve. **B** Formation of a neuroma post transfer of the ulnar nerve to the FCU branch of the ulnar nerve. This neuroma is further exacerbated by the eventual site of prosthetic harnessing for below elbow amputees. FCU, flexor carpi ulnaris.

protocol, progress is assessed using functional tests to track acclimatization.

Preoperative prosthetics protocol

The prosthetics team evaluates baseline EMG or myosite signals in the proximal musculature of the injured limb, which are crucial for future prosthetic use. A three-dimensional printed preliminary hybrid prosthetic is created to help in adaptation to use in daily living and strengthening the proximal musculature. Prosthetic options are also reviewed with the patient to confirm the optimal level of amputation, maximizing each patient's functional goals.

Preoperative psychology protocol

An initial psychological evaluation ensures that the patient is ready to proceed with an elective amputation by assessing the patient's current struggles and discussing embodiment. Limb loss can shape one's view of self and elicit feelings of anger, hostility, guilt, and poor self-image.[11] Prosthetic embodiment has been shown to have a positive impact with improvement in pain and overall physical integrity.[12] Embodiment education offers a positive outlook that may negate potential negative psychological outcomes. The preoperative care of these patients requires time, as the patient must be comfortable with their decision to pursue elective amputation. The robust physical training protocol may take up to 3 months, with further optimization of mental health prior to surgery requiring a longer presurgical course.[6]

SURGICAL TECHNIQUE

The technique for transradial amputation has evolved to the current standard of care, which provides a well-padded, pain-free residual limb, ideally free of phantom limb syndrome or residual limb pain by using nerve reconstructive techniques.[9,13,14]

Targeted muscle reinnervation for transradial amputation has become standard with well-published outcomes, and previous techniques for TMR in the setting of trans-radial amputation have been well-described.[13,15–18] Published techniques can be further optimized after shared experience demonstrates a potentially high complication rate associated with the ulnar nerve to ulnar nerve branch to flexor capri ulnaris TMR site. This site can often be compressed with prosthetic application and wear, creating an ongoing source of pain.[13] In more extreme situations, this transfer can lead to painful neuromas in a sensitive region of prosthetic harnessing (Fig. 1A, B).

Surgery is performed under general anesthesia without long-acting paralytic agents. The patient is positioned supine with the extremity extended on a hand table. An upper arm tourniquet is placed in a nonsterile fashion. The level of osteotomy is determined by subtracting 22.5 cm, which is the desired length of the prosthetic components, from the length of the contralateral limb from the lateral epicondyle to the thumb tip (with the elbow flexed at 90 degrees; Fig. 2). This measurement is the residual limb length drawn distal to the lateral epicondyle on the surgical extremity, including soft tissue (Fig. 3). These measurements are determined before surgery in conjunction with the prosthetist by demonstrating differing lengths of

FIGURE 2: Contralateral arm is measured with elbow flexed at 90^{o} from thumb tip to lateral epicondyle—16.5 in. in this patient. The average components length is 8.75 in. Residual limb length is 7.75 in. (16.5−8.75 in.) in this patient.

FIGURE 3: Level of soft tissue amputation 10 cm proximal to ulnar styloid. This corresponds to 7.75 in. residual limb length (20 cm from lateral epicondyle).

prosthetic components to the patient; if a patient desires a different set of components, the measurements are adjusted accordingly. A fish-mouth incision is designed with the volar and dorsal aspects 1−2 cm longer to offset the incision from the terminal point of the residual limb (Fig. 4).

The incisions are made under the tourniquet, and dissection is carried out to the muscle fascia while identifying sensory nerves. After the muscle fascia is incised, the radial and ulnar arteries are ligated proximal to the planned osteotomy levels (Fig. 5). The median, ulnar, lateral antebrachial, and radial sensory nerves are identified. Using intraoperative nerve stimulation, the recurrent motor branch of the median nerve is identified and separated from the remainder of the median nerve using microsurgical instrumentation. Internal neurolysis of the ulnar nerve separates the nerve into its three main components—the main sensory fascicles, the motor fascicles, and the dorsal cutaneous sensory fascicles. The nerves are then transected as distally as possible and tagged for future

FIGURE 4: Fish-mouth incision.

TMR/RPNI. Alternatively, the full median nerve can be divided for future transfer into the anterior interosseous nerve (AIN) (Fig. 6). The extensors are divided until the radius and ulna are reached. The superficial and deep flexors are divided distally until the pronator quadratus (PQ) is visualized. The muscle is dissected subperiosteally off the radius and ulna while preserving the anterior interosseus artery and nerve. The AIN is traced proximally from the PQ and divided. This pedicled muscle flap is preserved for future median nerve TMR (Fig. 7). Multiple 3.0 × 1.0 × 1.5 cm muscle grafts are harvested from the distal amputation stump for future RPNI. The ulna and radius are identified and cut 1.0−2.0 cm proximal to the skin cut, 0.5 cm offset from one another (Fig. 8). To complete a myodesis, drill holes are made into the radius and the ulna. The flexor musculature is sutured to the drill holes to cover the exposed radius and ulna, and the extensor musculature is then draped over the flexor musculature and sutured.

The recurrent branch of the median nerve to AIN transfer is performed with 9-0 nylon suture, and the remainder of the median nerve is treated with RPNI technique to control axonal escape. By performing the recurrent branch neurolysis and coaptation, a better size match to the AIN is achieved (Video S2, available online on the *Journal*'s website at www.jhandsurg.org) than traditional techniques. This allows for an avoidance of size mismatch, directed motor axon regeneration, and better signal quality of the resulting TMR myosite. If the median nerve is treated *en bloc*, the AIN is sutured to the center of the median nerve, and the PQ is then wrapped around the coaptation to prevent axonal escape and sutured to itself (Fig. 9). The RPNI technique includes suturing the epineurium to the center of the muscle graft using 6-0 nonabsorbable sutures, followed by the muscle graft being wrapped around the coaptation and sutured to itself with

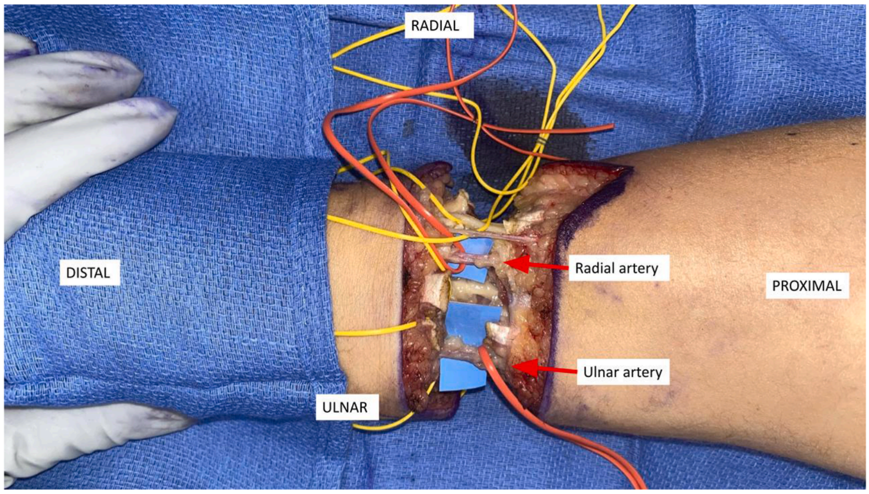

FIGURE 5: Dissection through skin and flexor tendons, taking care to dissect free all neurovascular structures. Radial and ulnar artery are ligated.

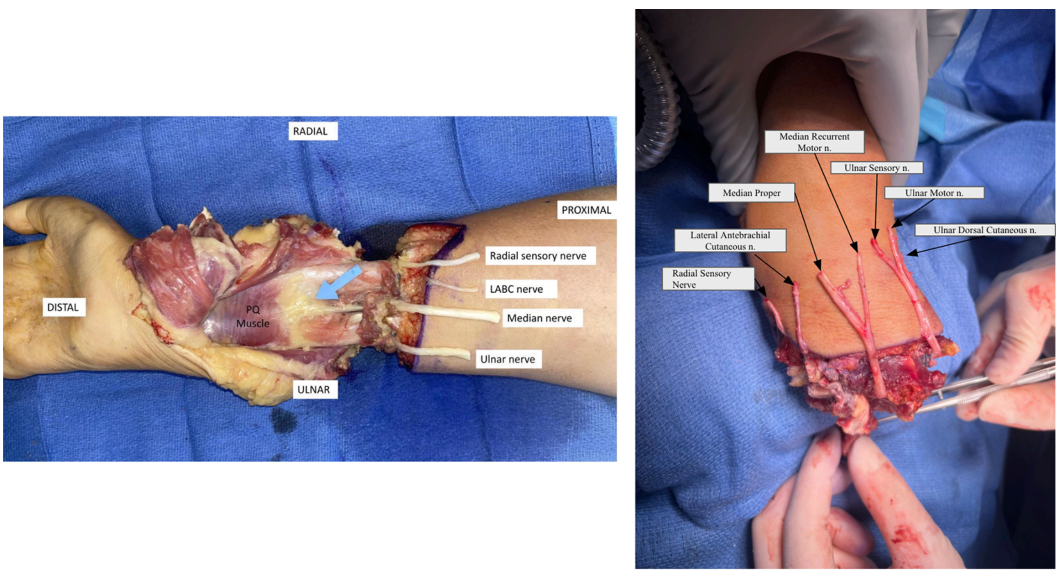

FIGURE 6: Dissection through muscle bellies and extensors, the distal forearm is split longitudinally to carpal tunnel to expose PQ muscle. Nerves are cut distally to preserve length. Blue arrow denotes anterior interosseous nerve and artery. LABC, lateral antebrachial. Left panel is a patient with full median and ulnar nerves divided, right panel is a different patient with internal neurolysis of median and ulnar nerves performed.

absorbable suture (Fig. 10). Three individual RPNI are used for the ulnar nerve fascicles. The recurrent motor to AIN-PQ TMR site and the ulnar motor RPNI site (Fig. 11) allow for intuitive grip triggers, allowing a patient think of thumb opposition to move into tripod grip and thumb adduction to move into lateral key pinch grip (Video S2). Regenerative peripheral nerve interfaces are also performed on the radial sensory branch and lateral antebrachial for a total of five RPNI and one TMR procedures. Each of these RPNI is buried under the skin in different marked locations. The tourniquet is released and hemostasis is achieved. The fish-mouth incision is closed in multiple layers under a compressive dressing (Fig. 12). The surgical technique described within this section is illustrated within Video S2.

Near-immediate postoperative prosthetic design and implementation

The prosthetic team fits each patient with a near-immediate postoperative prosthetic (NIPOP) during their initial 2- to 3-day hospital stay or prior to their first follow-up, adhering to the "30-day golden period."[19] Recently, myoelectric NIPOPs have been

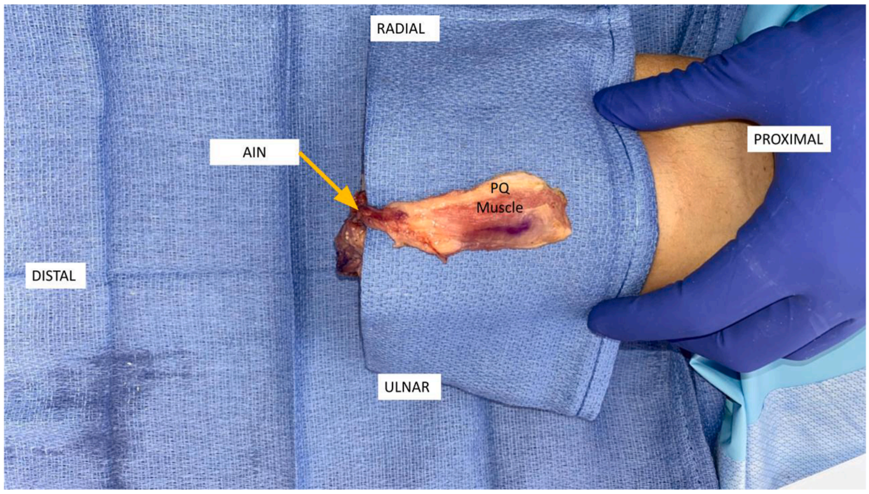

FIGURE 7: Pronator quadratus muscle is dissected off the radius and ulna to preserve neurovascular pedicle.

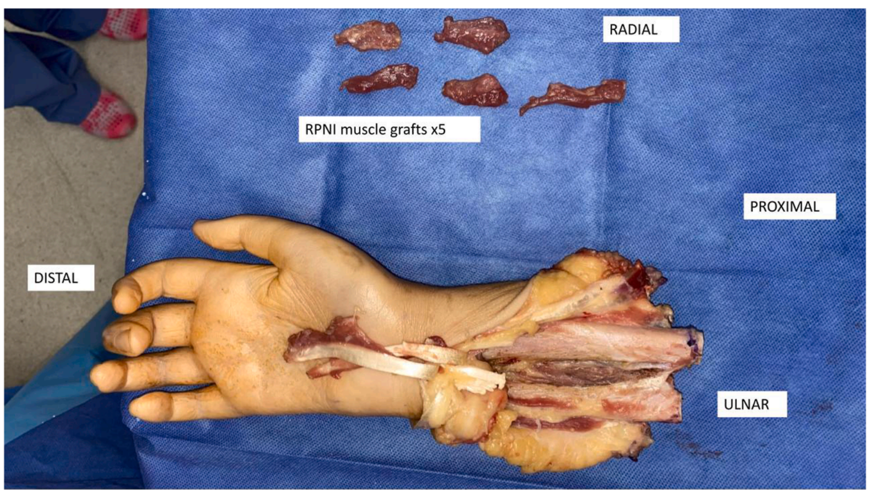

FIGURE 8: Osteotomies of radius and ulna performed to remove hand. Five muscle grafts are taken as RPNI for eventual neuroma prevention.

implemented, allowing for the early activation of myosite signaling and more robust prosthetic control.

Postoperative evaluation and technique

Postoperative rehabilitation protocol: Rehabilitation begins 3–7 days posttransradial amputation with a focus on wound care, desensitizing the limb, and reshaping the limb while monitoring swelling. Then, the therapy team teaches patients exercises such as integrated motor therapy and graded motor imagery. The NIPOP is used in therapy where patients learn to open and close the hook to practice grasping objects. Further progression includes the maintenance of grasp, strengthening grip, and practicing appropriately timed releases. Once an adequate level of proficiency is achieved, the therapy team shifts to teaching patients on using the NIPOP to complete activities of daily living such as using utensils, reaching across and above themselves, and performing bimanual tasks.

After an appropriate definitive myoelectric prosthetic is constructed according to patient-specific requirements, training focuses on optimizing the patient's proficiency, including exercises that primarily strengthen myosite signals and improve speed, precision, and quality of the motions. Repetitive motions are practiced during sessions, and patients are encouraged to use their definitive myoelectric prosthesis to complete complex tasks to return to normalcy.

Postoperative prosthetics protocol: The prosthetics team works with physical and certified hand therapists to reduce edema and reshape the limb by fitting the patient with a shrinker. Once swelling subsides, the

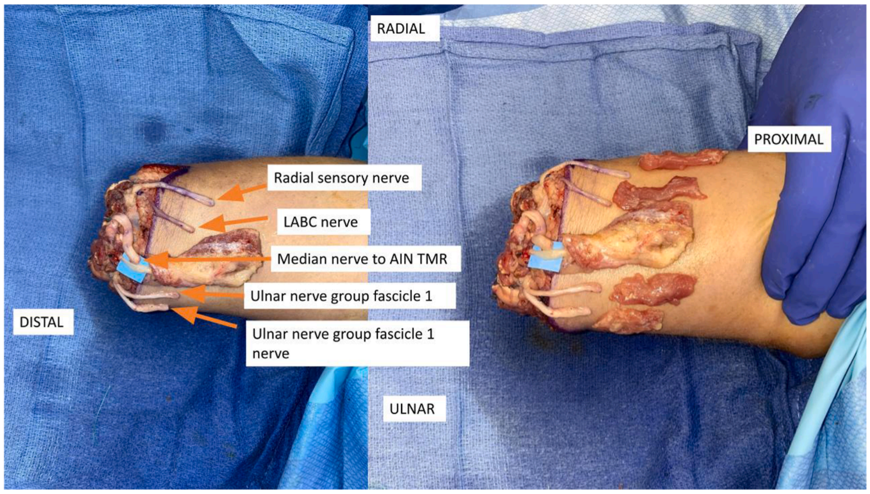

FIGURE 9: The ulnar nerve is divided into group fascicles. The median nerve is sewn to distal AIN after division of nerve as TMR. LABC, lateral antebrachial cutaneous nerve.

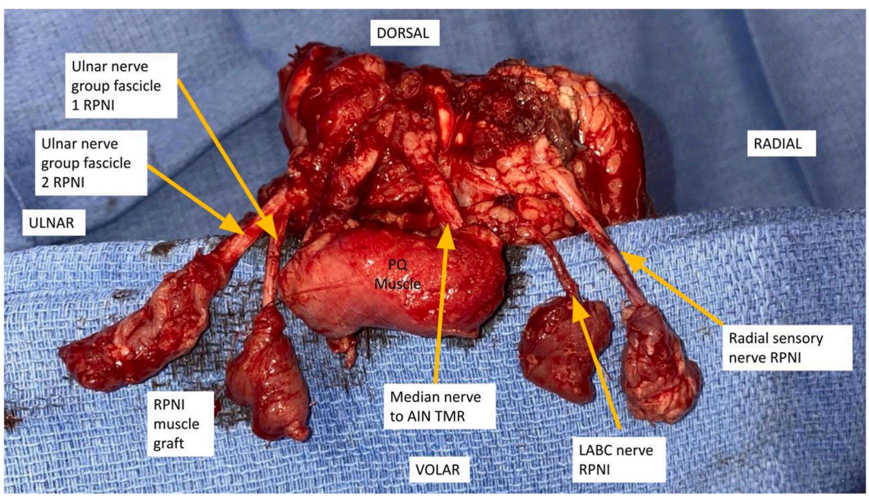

FIGURE 10: Final TMR and RPNI presurgical closure. LABC, lateral antebrachial cutaneous nerve.

prosthetic team routinely monitors the hook, frame, and joints of the NIPOP to optimize comfort and utility. They also help patients in learning how to don and doff the NIPOP and monitor concerns with fit throughout the postoperative rehab process to deter long-term prosthetic abandonment.

After adequate therapeutic progress, an assessment of limb maturation and stability is conducted to begin fit-testing for a definitive prosthetic. Patients are shown a multitude of devices and control strategies to accommodate individual goals. Control strategies are determined in concert with the hand therapy team to provide the patient with the best strategy to use their prosthesis.

Postoperative psychology protocol: The mental health team follows up with the patients to continue assessing their overall mental health with questionnaires such as Patient Health Questionnaire 9, the post traumatic stress disorder scale, and the Posttraumatic Growth Inventory. The patients can also connect with others who have undergone similar amputations in group therapy, which fosters a supportive and safe environment to aid rehabilitation. Individual therapy and psychiatric treatment are continued as determined by the mental health team. Psychological care throughout the entire process aids in optimal recovery.

CASE EXAMPLES/RESULTS

Case 1

A 52-year-old man presented to our multidisciplinary clinic 10 years after sustaining a traumatic left upper-extremity injury while at work. Following nine failed

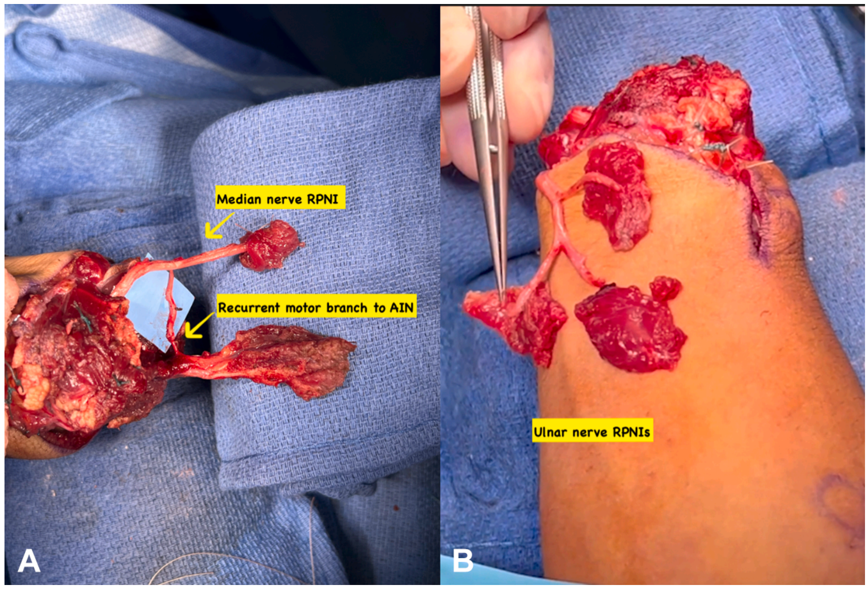

FIGURE 11: Recurrent motor branch of median nerve to AIN-PQ TMR site with median nerve proper treated with RPNI. Ulnar nerve sensory, motor, and dorsal cutaneous fascicles treated with RPNI.

FIGURE 12: Final closure of skin with superficial skin marking for future myoelectric signaling. MN, median nerve, UN, ulnar nerve.

reconstructive surgeries, the patient was left with a nonfunctional hand with severe chronic pain. The pain led to severe depression, substance abuse, inability to work, disconnection from his family, and multiple near-fatal substance abuse episodes. A plan for bionic reconstruction was proposed with an intense preoperative protocol, including hand therapy, prosthetics evaluation and treatment, and mental health evaluation with mandatory substance abuse treatment. The patient completed the preoperative protocol and underwent transradial bionic reconstruction as described above. He successfully participated in the postoperative protocols. Two years postprocedure, the patient is free from pain and substance abuse, is no longer on narcotic pain medication, and uses a myoelectric prosthetic for 6−8 hours daily. The patient returned to meaningful employment and successfully reintegrated into society (Video S3, available online on the *Journal*'s website at www.jhandsurg.org).

Case 2

A 33-year-old woman developed sepsis and was placed on extracorporeal membrane oxygenation after a group A Streptococcus infection following her second childbirth. She nearly died, experiencing pressor-induced necrosis of the left lower extremity and right thumb after resuscitation. Her right hand became contracted, painful, and nonfunctional despite hand therapy for several months. Due to the severity of her condition, bionic reconstruction was recommended. After completing the preoperative protocol and psychological treatment, the patient continued with transradial amputation and nerve reconstruction. During surgery, her deep musculature was found to be necrotic, and therefore, RPNI was used as the primary method of nerve reconstruction, including for the median nerve. She completed postoperative protocols and uses her immediate postoperative prosthetic, with a definitive myoelectric prosthesis recently fit and delivered (Video S4, available online on the *Journal*'s website at www.jhandsurg.org).

Case 3

A 29-year-old man presented 15 months after a motor vehicle accident with multiple burns to his left hand and an untreated lower trunk brachial plexus injury. After surgery for the burns at an outside hospital, the patient was left with a contracted, painful, nonfunctional hand. Due to his C8/T1 root avulsions, chronic pain improvement was deemed unlikely. After being evaluated, bionic reconstruction was proposed. After completing the preoperative protocol and psychological treatment, the patient underwent transradial amputation and nerve reconstruction using the described technique. One year postamputation, he uses a myoelectric prosthetic for 8 hours daily at work and at home, demonstrating significant increases in functionality compared with the preoperative nonfunctional hand (Video S5, available online on the *Journal*'s website at www.jhandsurg.org). Subjectively, his pain has improved despite the persistence of his brachial plexus injury.

EXPECTED OUTCOMES AND DISCUSSION

A successful outcome after bionic reconstruction includes the lack of neuropathic or phantom pain and the effective use of a prosthetic to maximize function. Although there exist previous descriptions of transradial amputation with differing forms of nerve reconstruction, there does not exist a singular technique of bionic reconstruction of the painful nonfunctional hand incorporating a hybrid of TMR and RPNI that provides complete coverage of all potentially exposed fascicles. The provided technique, using internal neurolysis of the recurrent motor branch of the median nerve, provides nerve coaptation without size mismatch that is found in traditional forms of TMR—this will diminish the potential for neuroma formation related to the TMR itself. Furthermore, there are no available comprehensive multidisciplinary protocols to optimize outcomes.

Although single- and dual-site activation control prostheses have reliable function at the transradial level, neuroma or phantom limb pain after amputation leads to decreased satisfaction with the use of prostheses and subsequent poor functioning both physically and from a psychosocial standpoint.[20,21] Targeted muscle reinnervation and RPNI have demonstrated efficacy in diminishing phantom and residual limb pain and can expand the options for prosthesis control by transferring transected nerves that no longer have a function to residual motor nerves that control functionally redundant musculature.[9] This causes an increase in the number of detectable signals for the prostheses, which in turn allows for increased utility of pattern recognition technology as a control strategy.[9] Our technique provides a unique opportunity for both functional reconstruction as well as pain relief for patients who have otherwise exhausted all "traditional" reconstructive options. Furthermore, the direct coaptation of the neurolysed recurrent motor branch of the median nerve to the anterior interosseous nerve is the first to provide a directed TMR site for independent thumb control, without fascicular mismatch, for when prosthetic technology can accommodate it. This, in combination with evolving control mechanisms that can potentially harness RPNI sites, would allow for true independent thumb function using both the recurrent motor branch of the median nerve to AIN-PQ TMR site for thumb abduction and the ulnar motor branch RPNI site for thumb adduction. As demonstrated in Video S2, these TMR and RPNI sites now allow for intuitive grip triggers, which simulates independent thumb function.

A multidisciplinary approach with structured perioperative care and rehabilitation provides a long-term commitment to improving patient outcomes. Previous models have successfully demonstrated that a multidisciplinary approach can prove a benefit for patients who have undergone amputations.[22] Integration of these systems into one clinic allows for comprehensive coverage of all facets of care for the complex problem that is the nonfunctional, painful hand. Long-term goals not only include the treatment of pain and loss of function but also mitigate prosthetic abandonment, which can be prevented through proper integration of the multidisciplinary team early on within the process.[22] The rehabilitative team provides early desensitization, wound management, proximal strengthening, integration, and flooding of the hybrid TMR/RPNI, and incorporation of the NIPOP for early bimanual dexterity. The NIPOP is fabricated by the prosthetics team to reduce the risk of a protracted rehabilitation program and allows patients to return to function faster, compared with traditional methods that lead to a long period of inactivity, profound loss of muscle mass, coordination, and fitness.[19,23] Finally, the mental health team members will ensure continued treatment of psychological challenges related to the loss of the extremity.

COMPLICATIONS

This technique does not significantly alter the known morbidity of TMR or RPNI for transradial amputations. A generalizable complication related to these techniques is failure of the reinnervation, neuroma formation, or denervation of remaining muscle groups. The described technique should ideally reduce the rate of symptomatic neuroma formation.

CONFLICTS OF INTEREST

No benefits in any form have been received or will be received related directly to this article.

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