CASE REPOSITORY

A Novel Muscle Transfer for Independent Digital Control of a Myoelectric Prosthesis: The Starfish Procedure

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Control of independent digital flexion and extension has remained an elusive goal in myoelectric prosthetics for upper extremity amputees. We first performed a cadaver study to determine the feasibility of transferring the interossei muscles for each digit to the dorsum of the hand without damaging the neurovascular pedicles. Once this capability was ensured, a clinical case was performed transferring the interossei of the middle and ring fingers to the dorsum of the hand where they could serve as a myoelectric signal for a partial hand amputee to allow individual digital control with a myoelectric prosthesis. Before surgery, it was impossible to detect an independent signal for each interossei; however, after the surgery, signals were reliably detected, which allowed these muscles to serve as myosites for finger flexion using a myoelectric prosthesis and move each digit independently. This concept of salvaging innervated and perfused muscles from an amputated part and transferring them into the more proximal and superficial portion of a salvaged limb has broad applications for improved myoelectric prosthetic control. *(J Hand Surg Am. 2018;■(■):1.e1-e5. Copyright © 2018 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Amputation, electromyographic signal, interossei muscle transfer, myoelectric control, prosthesis.

Online Exclusive

Recent technological advances have led to significant improvements in upper extremity prosthetics. Despite these advances, myoelectric prosthetics are limited by the human-prosthesis interface. Currently, the only available and successful mode of interaction is via myoelectric control using surface EMG.[1] Signals are often limited by myoelectric cross-talk, or unwanted detection of signals from adjacent muscles.[2] The use of implantable myoelectric sensors is an alternative strategy to detect myoelectric signals from muscle contractions. Whereas the concept of implantable myoelectric sensors is very appealing, they are not at present commercially available.

Currently, limited options exist for individuals having undergone partial hand amputations. Mechanical fingers of myoelectric hands are capable of independent finger flexion and extension, yet the requisite muscle signals for intuitive control are lacking. Amputation level determines the muscles available for surface EMGs[3] and, in turn, the ability to control multiple degrees of freedoms. Typical myoelectric partial hands consist of 2 or 3 surface electrodes that capture signals from either intrinsic hand muscles or extrinsic forearm muscles. Wrist and finger flexors control hand closure and extensor

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muscle groups control hand opening as a unit (all fingers simultaneously open and close).[4] When using intrinsic muscles to power myoelectric partial hands, the required movements are very unnatural because the requirement is to simulate digital abduction for finger opening and adduction for closure. Although forearm musculature produces reliable signals, prosthetic control is also unnatural because wrist flexion is required for grasp and wrist extension is required for release.[5] Furthermore, to capture signals from forearm musculature, the sensors must be placed more proximally than necessary, potentially impeding existing wrist function.

For pure signal detection of 1 muscle's contractions (and, hence, 1 desired function), ideally 1 myoelectric sensor is positioned to detect electrical signal from a single muscle. When multiple muscles and sensors are close to one another, the electrical signal generated by 1 muscle can be inadvertently detected by a neighboring sensor. This may result in accidental, undesired prosthetic function and is referred to as myoelectric cross-talk. This can be highly disruptive to a system designed to have 1 muscle sending a signal to 1 sensor. Spacing pairs of muscles and sensors apart from one another is 1 strategy to reduce myoelectric cross-talk. Maximizing the proximity of each individual sensor with its associated muscle also optimizes signal strength and purity. Finally, interposing nonmuscular tissue between adjacent sensors can reduce unintended signals from reaching a neighboring sensor. In this report, we present a case using 2 dorsal interossei (DI) muscle transfers to serve as independent EMG signals for individual digital control of a hand prosthesis. In addition, the flexor sheath and volar plate were interposed to minimize cross-talk. Prior to surgical treatment, a cadaveric study was performed to verify the procedural feasibility while maintaining the neurovascular pedicle. Before surgery, surface EMG signals for each interossei were measured and found to be inadequate. After surgery, independent surface EMG signals from the transferred muscles were reliable and individual control of 3 separate myoelectric fingers was attained. This concept of salvaging innervated, perfused muscles during amputations and transferring them into the more proximal salvaged limb has broad applications for improved myoelectric prosthetic function.

CASE REPORT

A pilot cadaveric dissection was performed on 2 fresh-frozen cadavers under loupe magnification to identify all hand intrinsic muscles with their neurovascular pedicles to determine the feasibility of the planned procedure. The ability to transfer all hand intrinsic muscles dorsally within the hand and even the distal forearm, while maintaining their neurovascular pedicles, was assessed. An additional goal was to identify the optimal interposition tissue to prevent myoelectric cross-talk.

In the cadaveric study, the radial and ulnar arteries were dissected from the distal forearm to the common digital arteries. Contributions to the palmar arches and direct pedicles into hand intrinsic muscles were identified. Next, the median and ulnar nerves were dissected from the distal forearm until all terminal branches to hand intrinsic muscles were identified. The thenar muscles, hypothenar muscles and all interossei were then elevated and mobilized from their origins and insertions. The metacarpals (MPs) were resected 3 cm proximal to the metacarpophalangeal (MCP) joints to simulate the required space for prosthetic components and all intrinsic muscles were easily transferred dorsally without tension on the neurovascular pedicles. The flexor tendons, extensor tendons, volar plates, and flexor sheaths were mobilized and used as interpositional spacers to prevent cross-talk. The volar plates and flexor sheaths appeared most suitable in terms of bulk and ease of mobilization. With further dissection of the neurovascular pedicles, we were able to perform a wrist disarticulation and mobilize the entire complement of thenar, hypothenar, and interossei muscles to the level of the distal forearm. The resultant appearance of the transferred hand intrinsic musculature resembles a starfish (Fig. 1). This appearance coupled with the ability of starfish to regenerate lost limbs led us to term this the starfish procedure.

A 39-year-old man sustained an avulsion injury with complete amputations of the left middle, ring, and little fingers through the MCP joints. He underwent replantation initially with subsequent failure necessitating amputation (Fig. 2). The digits were completely avulsed from the hand and forearm. The flexor tendons were avulsed from the musculotendinous junctions in the forearm well proximal to the level of the skeletal injury. Novel muscle transfers were planned to obtain separate and distinct myosignals for enhanced myoelectric prosthetic use. Before surgery, the third and fourth DI muscles' surface EMG signals were evaluated using the Ottobock MyoBoy (Duderstat, Germany). With assistance from a prosthetic component manufacturer (Vincent Systems GmbH, Karlsruhe, Germany) and a software engineer, prosthetic components were designed with multiple EMG inputs and motor drivers to allow intuitive individual digital control. Specifically, the aim was to obtain separate signals from each fingers'

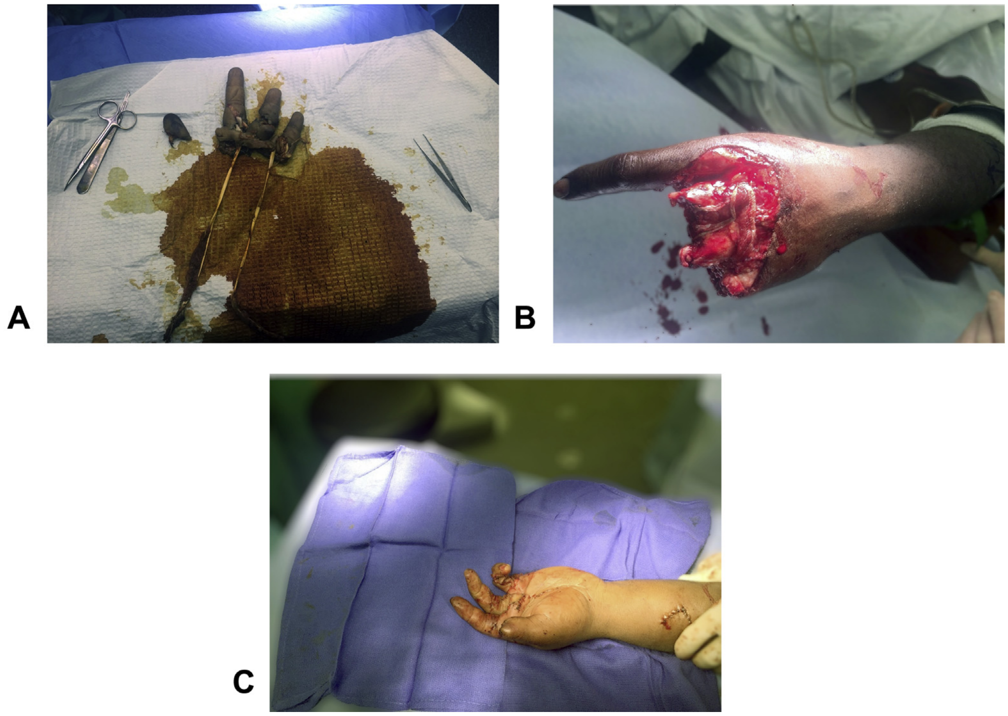

FIGURE 1: **A** Clinical image of the amputated middle, ring, and little fingers as well as the tip of the thumb. **B** Clinical image of the injury resulting in amputations of the middle, ring, and little fingers as well as the tip of the thumb. **C** Clinical image immediately following replantation of 2 digits. Subsequent digital ischemia necessitated revision amputation

intrinsic musculature to power individual digital flexion. Because these interossei naturally flex the MCP joints, individual, intuitive digital control was anticipated.

The surgical technique utilized began with disarticulations of the middle, ring, and little fingers performed through the MCP joints. Incisions were extended proximally to expose the MPs and interossei. The third and fourth dorsal and second and third volar interossei (VI) muscles were mobilized in a distal to proximal direction, releasing them from the MPs. The MPs were resected 3 cm proximal to the MCP joints to allow prosthetic component space. Next, the volar plates and flexor tendon sheaths from the ring and little fingers were mobilized and rotated dorsally. The third and fourth DI muscles were then positioned onto the dorsum of the third and fourth MPs and sutured to the surrounding periosteum to maintain resting length. The volar plates and flexor sheath flaps were interposed and sutured to the extensor tendons to minimize myoelectric cross-talk (Fig. 3).

The DI muscles are typically selected for dorsal transfer, and with careful dissection, these muscles can be separated from the VI muscles without sacrificing the neurovascular pedicle to either muscle. An important concept to consider is that the VI muscles serve to initiate MP flexion to a different digit than

FIGURE 2: All intrinsic muscles have been dissected free of all surrounding tissue maintaining the neurovascular pedicles. The resultant starfish appearance is noted.

the DI muscles that they accompany and to which they are just palmar. For example, the fourth DI muscle, which is intimate with the third VI muscle, acts to initiate ring finger MP flexion (as well as ring finger abduction). The third VI muscle, however, assists in the initiation of little finger MP flexion (as well as little finger adduction). Therefore, if the desired muscle transfer is aimed at creating an intuitive control for ring finger MP flexion, then the fourth DI muscle should be dissected free from the

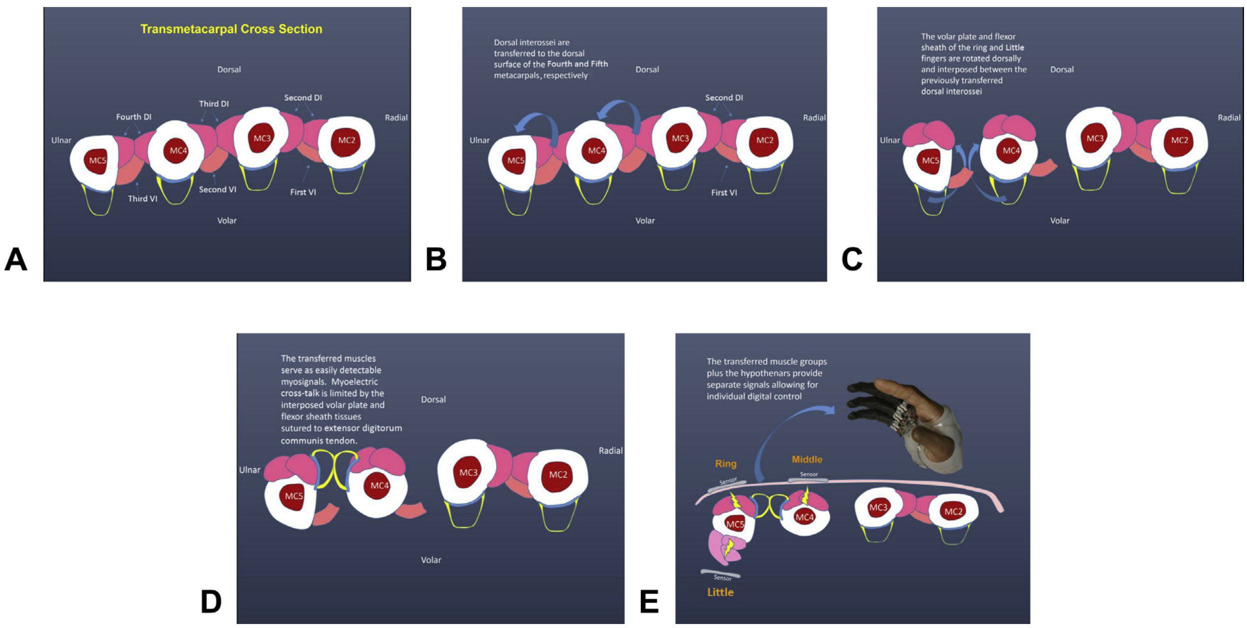

FIGURE 3: A–E These cartoons demonstrate an axial view of the surgical technique beginning with identification of the interossei, dorsal transfer of the DI muscles, interposition of the volar plate and flexor sheath, and finally, application of the surface electrodes outside the skin to detect the signals.

third VI muscle, and only the fourth DI should be transferred dorsally. For little finger MP flexion, a surface electrode over the hypothenar musculature to detect flexor digiti minimi is desired when possible. In cases in which the hypothenars are not available, the third VI muscle may be mobilized and transferred to the subcutaneous region to serve as the intuitive signal for little finger prosthetic flexion. It is an important technical aspect of the starfish procedure to separate the VI and DI muscles because, if they are transferred together, conflicting signals will be sent to the overlying surface electrode because the muscles naturally act on different digits.

Before surgery, the third and fourth DI muscles were found to have a surface EMG signal measuring 4 microvolts (μV), which is far too low for meaningful myoelectric control. Fourteen days after dorsal transfer, the signals increased to 58 μV and were palpable as individual signals for each set of transferred interossei with minimal cross-talk. Less than 1 month later, without any therapy or prosthetic training, the patient demonstrated individual digital control on a simulated partial hand prosthesis. This highlights the remarkably intuitive ability to control individual digital motion following the transfers and the tremendous signal strength achieved for each muscle (Video A; available on the *Journal*'s Web site at www.jhandsurg.org). Mirror box training was then used to improve the ability to independently activate the signals, and 6 months later, independent signals were easily activated with a strength of 100 μV. Once the custom prosthesis was complete, the intuitive nature of the transfers was readily apparent because the patient immediately demonstrated individual finger control (Video B; available on the *Journal*'s Web site at www.jhandsurg.org).

Currently, the patient is 24 months from surgery. He has had his prosthesis for 10 months. In addition to individual digital control, the patient is capable of flexing any combination of 2 digits or all 3 digits simultaneously. He currently can lift a 20-lb dumbbell using this limb and his visual analog scale (VAS) pain score is 1.3.

One alteration to his prosthesis has been made since its original design: a locked grasp feature. Whereas the transferred interossei generate excellent independent signals, fatigue was an issue with higher-demand activities requiring prolonged grip. This resulted in unwanted digital release over time. To allow the hand to lock in a grip position, the prosthesis was programmed to allow 2 rapid consecutive flexion signals to trigger closure of all digits (the patient fires the interossei twice rapidly and the hand closes and remains locked in a grasp position). This closure is maintained until the same pattern of rapidly contracting the interossei twice is repeated. This has improved higher-demand activities requiring prolonged grasp and has extended wear time by avoiding fatigue associated with sustained muscle contraction.

DISCUSSION

Despite advances in prosthetics, current devices cannot fully replicate the dexterity and capabilities of the human hand. In more proximal amputations, targeted muscle reinnervation provides additional signals for myoelectric control by transferring terminal nerve branches to proximal muscles. Using this technique, targeted muscle reinnervation has improved prosthetic outcomes in high upper extremity amputees.[6]

Transmetacarpal amputations currently have few functional prosthetic options. Myoelectric options are limited by the lack of available detectable muscle signals. Implantable multichannel wireless EMG signals may provide improved signaling and user interface in future myoelectric prosthesis but are not currently commercially available.[7,8]

In this case, the transferred DI muscles with flexor sheath interposition, in combination with a hypothenar signal, provided independent signals to power individual digital control of a myoelectric hand prosthesis. This concept of salvaging muscles with remaining nerve and blood supply from a mangled extremity and transferring them into a more proximal location during amputation has the potential to markedly enhance available signals for myoelectric detection and, hence, function.

This technique has the potential to create similar individual digital control for even more proximal level amputations. Our cadaver work demonstrates the potential for applying this concept to more proximal level amputations including the potential for a myoelectric hand with all 5 digits capable of independent control even with amputation at the level of the distal forearm.

The opportunity to salvage muscles that retain their nerve and blood supply and transfer them proximally in an amputated limb to allow increased myoelectric signals merits further research.

REFERENCES

1. Farina D, Jiang N, Rehbaum H, et al. The extraction of neural information from the surface emg for the control of upper-limb prostheses: Emerging avenues and challenges. *IEEE Trans Neural Syst Rehabil Eng*. 2014;22(4):797−809.
2. De Luca CJ, Merletti R. Surface myoelectric signal cross-talk among muscles of the leg. *Electroencephalogr Clin Neurophysiol*. 1988;69(6):568−575.
3. Schultz AE, Kuiken TA. Neural interfaces for control of upper limb prostheses: the state of the art and future possibilities. *PM R*. 2011;3(1):55−67.
4. Tenore FV, Ramos A, Fahmy A, Acharya S, Etienne-Cummings R, Thakor NV. Decoding of individuated finger movements using surface electromyography. *IEEE Trans Biomed Eng*. 2009;56(5):1427−1434.
5. Atzori M, Müller H. Control capabilities of myoelectric robotic prostheses by hand amputees: a scientific research and market overview. *Front Syst Neurosci*. 2015;9:162.
6. Dumanian GA, Ko JH, O'Shaughnessy KD, Kim PS, Wilson CJ, Kuiken TA. Targeted reinnervation for transhumeral amputees: current surgical technique and update on results. *Plast Reconstr Surg*. 2009;124(3):863−869.
7. McDonnall D, Hiatt S, Smith C, Guillory KS. Implantable multichannel wireless electromyography for prosthesis control. *Conf Proc IEEE Eng Med Biol Soc*. 2012;2012:1350−1353.
8. Bergmeister KD, Hader M, Lewis S, et al. Prosthesis control with an implantable multichannel wireless electromyography system for high-level amputees: a large-animal study. *Plast Reconstr Surg*. 2016;137(1):153−162.