Shoulder Disarticulation Externally Powered Prosthetic Fitting Following Targeted Muscle Reinnervation for Improved Myoelectric Control

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ABSTRACT

Functional prosthetic restoration is challenging for individuals with high-level upper extremity amputations. It is of greater consequence when the individual has sustained bilateral limb loss. It is possible to denervate expendable regions of muscle in or near an amputated limb and transfer the residual peripheral nerves to this muscle. The surface EMG signals from the reinnervated muscle can then be used as additional control signals for an externally powered prosthesis. This technique, called "targeted reinnervation," allows the simultaneous control of multiple degrees of freedom in a prosthesis. Control of the prosthesis is also easier and more natural because the myoelectric signals are physiologically correlated to the movements of the lost arm and could greatly improve the function of myoelectric prostheses. The authors describe the first application of targeted reinnervation to a man with bilateral shoulder disarticulation amputations, with a focus on the prosthetic fitting and its challenges. The surgical procedure and preliminary outcomes are presented. (*J Prosthet Orthot*. 2006;18:28–34.)

KEY INDEXING TERMS: control, myoelectric, reinnervation, shoulder disarticulation

The restoration of function in shoulder disarticulation patients is very challenging. Externally powered terminal devices, wrists, elbows, and shoulder locks are available, but the options for controlling these devices are quite limited. Generally only one degree of freedom can be controlled at a time with myoelectric signals or touch pad systems. In an attempt to improve functional control of myoelectric prostheses, an effort has been made to study the possibility of transferring the residual nerves to spare muscles in or near the residual limb. These nerves are used to reinnervate targeted muscles, and then surface myoelectric signals from these muscles can be used to simultaneously control multiple degrees of freedom in the prosthesis.[1,2] Furthermore, if successfully transferred and usable in a clinical setting, the nerves would be controlling functions in the prosthesis that they controlled in the natural arm, making operation of the device easier and more natural.

In the shoulder disarticulation amputee, there are four remaining distal brachial plexus nerves: the musculocutaneous nerve for control of elbow flexion; the median nerve, which primarily controls hand and wrist flexion activities; the radial nerve that controls extension activities of the elbow, wrist, and hand; and the ulnar nerve, which controls some wrist flexion and finger abduction activity. These nerves, if transferred to separate regions of the pectoralis muscles, could potentially provide four or more independent myoelectric control signals to simultaneously operate a powered prosthetic terminal device, wrist, and elbow.

Research into this concept has been promising. Studies have shown that when large nerves (such as brachial plexus nerves) are transferred onto relatively small muscle areas, the recovery of the muscle is very good.[3] Computer simulations have indicated that it should be possible to record independent myoelectric signals from several muscle areas with electrodes spaced only 2 to 3 cm apart, especially if the patient's subcutaneous fat is removed.[4,5] Finally, computer-controlled, upper-limb prostheses are now available that allow many different inputs to control multiple motors.[6]

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A unique patient came to us who was appropriate for targeted muscle reinnervation. A 54-year-old man presented to the Rehabilitation Institute of Chicago (RIC) for prosthetic fitting of bilateral shoulder disarticulation prostheses. This patient had sustained severe burns secondary to electrical injury that required immediate amputation approximately 7 weeks before his visit.

The amputations had been performed at the "true" shoulder disarticulation level, with the humeral head absent and the shoulder girdle fully intact (Figure 1). The patient was initially fit with a body-powered prosthesis on the right side and an externally powered prosthesis on the left using a touch pad control system. The patient had split-thickness skin grafts in his bilateral axillary regions that remained hypersensitive, and excision was recommended by his primary surgeon. This presented the opportunity to perform targeted muscle reinnervation procedures during this surgical intervention, as described by Kuiken et al.[7] We describe his initial prosthetic fitting, briefly outline the surgical intervention, and describe the development of the experimental prosthesis.

CONVENTIONAL INITIAL FITTING

Prosthetic options were discussed with the patient and his wife, who provided relevant feedback regarding the design of the prostheses. The patient demonstrated the motivation necessary to partake in the difficulties of fitting and training an individual with such high-level prostheses. A recommendation was made to provide this patient with bilateral shoulder disarticulation prostheses. A body-powered design was provided for the more dominant right side, whereas an externally powered design was used for the left. The philosophy at the RIC (mirroring that of several other centers that fit individuals with high-level upper extremity amputations) is to use different styles of prostheses on the two limbs. Varying designs enable the amputees to perform fine motor grasp functions with the body-powered prosthesis, and gross/power functions with the externally powered prosthesis.

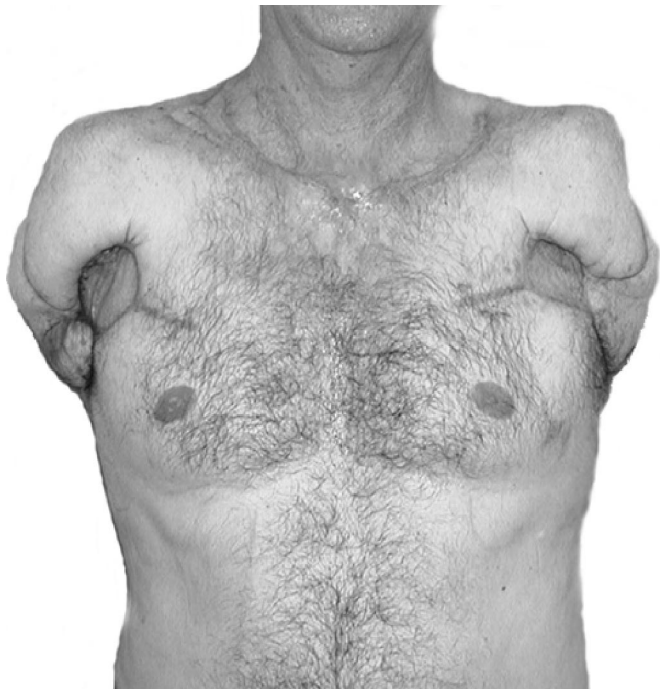

Figure 1. Patient with bilateral shoulder disarticulations.

The left externally powered prosthesis was originally designed using conventional force sensitive resistor (FSR) control. It consisted of an LTI-Collier locking shoulder (Liberating Technologies, Inc. [LTI], Holliston, MA), friction humeral rotator, a Boston Digital Arm (LTI) for the powered elbow and controller, an Otto Bock powered wrist rotator, and an Otto Bock Greifer for the terminal device (Otto Bock Healthcare US, Minneapolis, MN). The control scheme was designed with FSR activation for several reasons. The mobility of the glenoid region through protraction, retraction, elevation, and depression enabled us to find multiple sites for positioning the FSRs. The patient had a well-defined acromion that would enable FSR selection of closely spaced pads. In addition, there were reasons not to attempt myoelectric fittings. Myoelectric control is possible at this level of amputation; however, with our initial options for electrode placement, it would have been difficult to harness the patient as tightly as needed for good electrode contact because he had painful scarring on both of his lateral chest walls. Impressions of his residua were taken via a circumferential casting method. Care was taken in several areas on the cast, including regions anterior to the glenoid area, superior pectoralis, supraspinous regions of the scapulae, superior trapezius, and circumferentially around the waist. The regions anterior to the glenoid area were compressed to permit transmission of forces to the sockets during operation of the body-powered prosthesis. The left socket would require additional modification to enable these forces to be transmitted without contacting the FSRs that would be incorporated, thus avoiding inadvertent movement of the externally powered prosthesis. Superior pectoralis and supraspinous regions were molded in a wedge-shape fashion to enable the forces from the weight of the prostheses to be distributed to these regions, providing both an excellent means of suspending the devices and rotational control. The superior trapezius was also being used for the purpose of suspension and weight acceptance of the prostheses. Special attention was taken in these regions because scarring was present proximal to the neck bilaterally, leaving only a small region for this acceptance of weight. A minimal relief was made superior to the acromion process so the patient would not hit the FSRs inadvertently. Lastly, the waist region was molded to counteract the forces and moments created by these prostheses. Most important were the anterior and lateral regions of the distal impression because the forces in those regions would be occurring secondary to the arms being flexed and abducted, respectively.

The patient was fit with test sockets bilaterally upon his return to the RIC. These test sockets were modified for appropriate contact and relief. The left socket was marked for proper placement of the FSRs. The method of controlling the externally powered prosthesis would be to use four FSRs (Figure 2). Two FSRs were mounted anterior to the glenoid

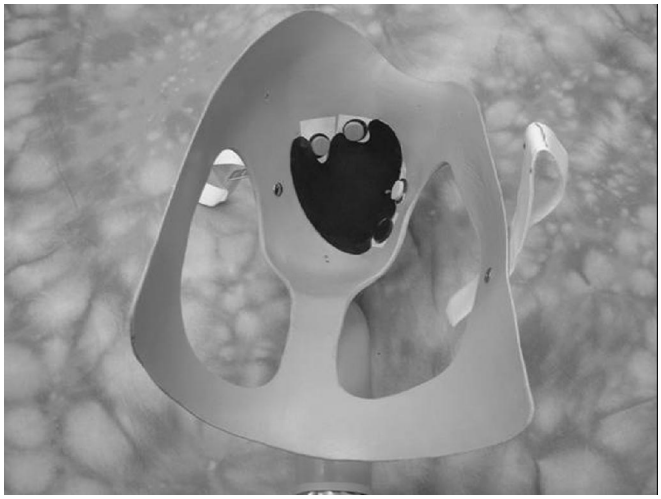

Figure 2. FSR placement in socket of conventional externally powered prosthesis.

region for independent control of the Greifer terminal device opening and closing. As mentioned, care had to be taken to place them in a position where they would not be contacted inadvertently during biscapular abduction, which was used for operation of the contralateral, cable-driven prosthesis. A third FSR was mounted superior to his left acromion process to control flexion and extension of the Boston Digital Arm. The FSR functioned in a servo-FSR fashion. If the patient wished to operate the prosthetic elbow, he would push against the FSR to flex the elbow. The harder he pressed, the faster the elbow would flex. When he eased off of the FSR, the elbow would extend proportionately to the rate of decreased force on the sensor. To hold the elbow in a position for a prolonged period, he pushed up into the FSR until the elbow flexed to the desired position and maintained this force (position of the elbow) for a defined period, allowing the elbow to go into "sleep mode." This amount of time could be varied and was adjusted by the prosthetists for optimal use by the patient. To extend the elbow from this static position, the user would have to generate a force on the FSR equal to or greater than that at which the elbow was locked. The elbow would "wake up," and then the patient could further flex or extend the elbow by increasing the force or easing up slowly on the FSR, respectively. Humeral rotation positioning was achieved in the conventional manner through a passive turntable with adjustable frictional control on the lamination collar of the Boston Digital Arm. An FSR was mounted posterior to his acromion, which was used for powered wrist rotation using the Otto Bock Electronic Wrist Rotator. A soft touch to the FSR would drive the wrist in pronation, whereas a hard touch would drive the wrist into supination. All of the FSR activations had proportional speed control, regardless of how the approach to the FSR activation was initiated. The LTI-Collier shoulder joint was controlled with a mechanical lock/unlock chin nudge switch (Endolite, Lock Release, 2-position; Endolite, Centerville, OH). This allowed the patient to passively preposition the shoulder in flexion and extension with the aid of gravity and lock it with the chin nudge switch. Abduction/adduction was positioned passively and held in place with friction. These components were mounted to a laminated, frame-type socket.

The right shoulder disarticulation prosthesis was a body-powered design with Hosmer-Dorrance 5XA terminal device (Hosmer Dorrance Corp., Campbell, CA), Sierra Wrist Flex Unit (Hosmer Dorrance), USMC Rotational Wrist Unit (USMC, Pasadena, CA), Hosmer-Dorrance E-400 Internal Locking Elbow, fair-lead cable with Spectra-cable and Teflon lining, LTI-Collier Shoulder Joint with mechanical lock, three chin nudge switches (two Sierra Nudge Control [Hosmer Dorrance] and one Lock Release, two-position [Endolite]), a sheave style excursion amplifier and frame-type socket. The Sierra Wrist Flex Unit and Rotational Wrist Unit were altered from their original designs to make the wrist function a modified version of the Four-Function Wrist Unit, as seen in previous designs by Kaywood and Robinson (unpublished). The Sierra Wrist Flex Unit had a large washer added to the unlock lever to enable ease of contact by the patient. This, combined with the offset angle of pull by the position of the cable and terminal device attachment post, allowed the user to flex the wrist with relative ease. Two screws were added along with a rubber band on the lateral aspect of this Sierra Wrist Flexion Unit to provide for spring-return wrist extension when the lever was depressed and the cable relaxed. The pronation and supination of the Sierra Wrist Flex Unit and 5XA terminal device were provided through action of the rotation wrist unit. As the patient activated the lever via one of his chin nudge switches, the modified inner wrist and spring-loaded inner housing would act to pronate the terminal device and wrist flexion unit. If the patient held the switch and simultaneously pulled the fair-lead cable, the wrist would supinate. All of the cable-driven functions (terminal device opening, wrist flexion, wrist supination, and elbow flexion) were operated through a fair-lead cable. The cable was made of Spectra-cable and fed through a Teflon lining inside of the heavy duty housing along with a sheave-type excursion amplifier. The body motion used to control these operations was biscapular protraction. The operation of the LTI-Collier shoulder joint lock was with a chin nudge switch with gravity-assisted flexion and extension as described.

The patient received several weeks of occupational therapy learning the various operations of the prostheses. He had the prostheses in a test socket stage while he was in Chicago and returned home with them for a month. Both prostheses were then returned via mail, and the cable-driven prosthesis was completely fabricated. The externally powered prosthesis was refit, and additional occupational training occurred at the fitting and delivery visit. By current standards, the patient did well with his prostheses. After the initial fittings, he was able to eat with his body-powered prosthesis. He was also able to pour liquid into a glass and don a cap with the externally powered prosthesis. However, these tasks were not very smooth because of the sequential control required to perform them. Information was shared with a local occupational therapist on how the

prostheses functioned so additional training could continue when the patient returned home. A local prosthetist was also given information on what components were incorporated into the prostheses in the event of repairs.

SURGICAL INTERVENTION

Shortly after his amputations, the patient was experiencing pain and discomfort in the areas where he had split thickness skin grafts; they had become hyperesthetic. Wearing his prostheses was uncomfortable, and even direct water pressure from showering was painful. It was recommended by his primary surgeon that he have surgery to remove the split thickness skin grafts. This presented the opportunity to perform targeted muscle reinnervation procedures during this surgical intervention. The patient had the potential for significantly improved prosthetic control and function if the nerve transfer procedure were successful. If the targeted muscle reinnervation were unsuccessful, his painful grafts would still be removed, he would still be able to use his first set of prostheses (without change), and there would be no significant harm to the patient. The decision was made to perform the nerve transfers only on the left side of the patient's chest on which he wore his externally powered prosthesis.

The surgery was performed following Institutional Review Board approval and consent of the patient. The right skin graft was excised first and closed. Then the left skin graft was excised and the surgical field opened. The brachial plexus nerves were identified and dissected free for reattachment to the pectoralis muscles. The clavicular head of the pectoralis major muscle was separated from the sternal pectoralis major muscle, and the sternal head was separated into upper and lower portions. The pectoralis minor was moved to the lateral chest wall so it could be used as a possible EMG control site and so that its EMG signal did not interfere with the other muscle regions. The pectoralis muscles were denervated, neuromas were resected from the residual peripheral nerves, and these nerves were attached to the isolated muscle segments. The musculocutaneous nerve was attached to the superior segment of the pectoralis major muscle, the median nerve to the middle segment, the radial nerve to the inferior segment, and the ulnar nerve to the pectoralis minor muscle. In addition, all subcutaneous fat was surgically removed over these muscle sites to achieve stronger EMG signals with less cross-talk. For greater detail about the surgery, see Hijjawi et al.[8]

After the surgery and recovery from postoperative pain (approximately 3 weeks), the patient was able to use his body-powered and FSR-controlled prostheses. During this "waiting period," the body-powered prosthesis had to be repaired by the local prosthetist because the activities this patient was performing caused component failure. The most dramatic failure occurred when he used his prosthesis to pull-start his riding lawnmower and detached the shoulder from the socket. Throughout this waiting period, the patient was encouraged to move his missing elbow, wrist, and hand with the thought that this strengthened his muscles once reinnervation occurred.

The first muscle activity appeared about 4 months after surgery in the clavicular head of the pectoralis major muscle, indicating successful reinnervation of the musculocutaneous nerve. After approximately 6 months of recovery were allowed, the musculocutaneous, median, and radial nerve-muscle transfers were successful in that muscle contractions could be seen and felt, and surface EMG could be recorded in three separate regions of the pectoralis major muscle. No contraction of the pectoralis minor muscle could be appreciated, indicating this nerve transfer was unsuccessful.

EXPERIMENTAL PROSTHETIC DEVELOPMENT AND FITTING

Extensive myoelectric testing was performed to locate and isolate independent, usable myoelectric signals. A very strong and independent signal could be recorded just under the clavicle when the patient attempted elbow flexion. This correlated, as expected, with the musculocutaneous nerve transfer. Surprisingly, two independent signals could be recorded from the middle pectoralis region where the median nerve was transferred. In the lateral area, a clear signal was recorded when the patient closed his missing hand. This correlates to the predominant flexion function of the median nerve. However, the patient could also independently contract a separate region in the medial portion of his middle pectoralis major muscle. He said he felt he was opening his hand or thumb. It is presumed that the branches of his median nerve that innervated thumb abductor muscles discretely reinnervated this area. There was co-contraction in the lower pectoralis major muscle with the other reinnervated muscle regions, significant ECG interference, and shifting of soft tissue as the muscles were contracted. Therefore, it was decided during this fitting not to use this radial nerve reinnervated region for control in the prosthesis.

The design of the second set of prostheses (Figure 3) was then begun. The right, body-powered prosthesis remained essentially the same in design; the only exception was the control mechanism by which the LTI-Collier shoulder joint was activated. An electronic lock/unlock feature was added to the design because it proved difficult to incorporate the mechanical switch without having breakdown of the gear teeth. This "wearing away" was caused by lack of complete "throw" of the chin nudge switch and thus an incomplete unlock of the shoulder joint.

With the experimental left prosthesis, transformation from FSR control to myoelectric control was undertaken with three electrodes incorporated into the socket. The first electrode was located just inferior to the medial clavicle over muscle reinnervated by the musculocutaneous (biceps) nerve. This was used for myoelectric control of the elbow in a "myo-servo" fashion; essentially, elbow flexion angle was proportionate to the myoelectric signal amplitude of this single muscle region. This was the first major sacrifice that we had made, in that we did not find

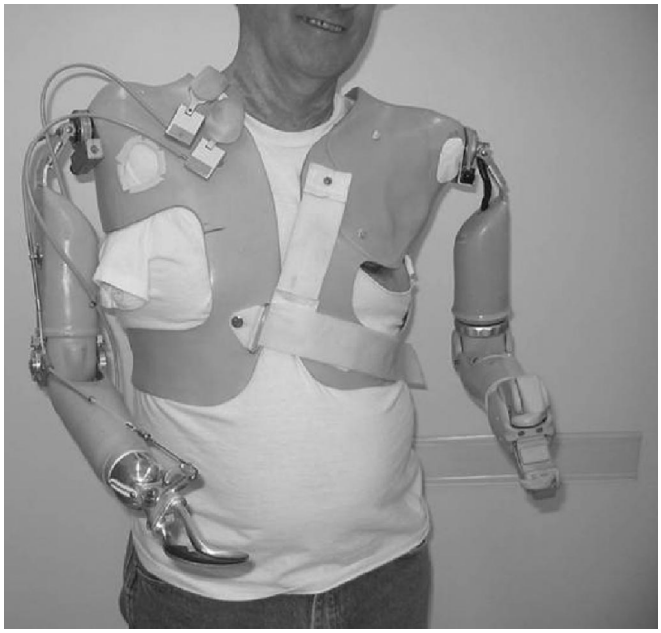

Figure 3. Experimental externally powered prosthesis on left side.

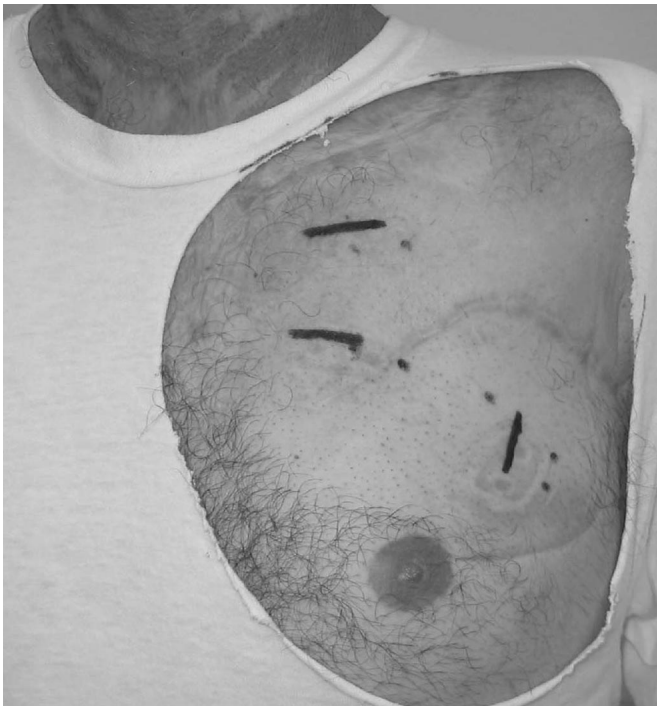

Figure 4. Location of electrodes on patient's chest.

a second, independent, usable site for elbow extension. However, we did design the elbow function similarly to that of concentric and eccentric elbow flexor contractions. As the muscle was contracted concentrically, the prosthetic elbow flexed. As the muscle eased off, as in an eccentric contraction, the prosthetic elbow made a controlled extension. The Boston Digital Arm contains a brushless motor with a reverse locking clutch. Because of this reverse locking clutch, gravity alone cannot extend the Boston Digital Arm; it must be driven by the controller. The electronics in the Boston Digital Arm sensed the difference between the maximum voltage output, which previously flexed the elbow, and a lower voltage output, which then drove the elbow into extension. The elbow would go into a "sleep" or locked mode if the patient held a position for a programmed period; he could then relax his muscle while maintaining the elbow position. To unlock the elbow, the patient generated a myoelectric signal of equal or greater size than that required for the locked position, and the elbow would return to a position controller.

A second electrode was mounted in an area approximately 8 cm inferior to the first electrode. This was used for hand opening. A third electrode was placed approximately 6 cm lateral to the second electrode and was used for hand closing (Figure 4). These latter two electrodes were used in the more typical fashion as two-site proportional input devices to the terminal device.

A single Otto Bock electrode was used for the control of the elbow in a myo-servo fashion. The other two electrodes being used were the Liberating Technologies "packaged AC electrodes" in-socket, myo-electrode amplifiers. ECG interference was also an issue with the electrodes in the midpectoral region (the median nerve transfer region). The thresholds for the open and close myoelectric signals had to be set higher than desired to prevent the ECG from interfering with terminal device function. One of the major challenges in the prosthetic development was maintaining contact between the electrodes and the skin. The skin and muscle in the newly reinnervated pectoralis region were very mobile. Because the targeted muscle segments were surgically separated, contraction of these muscle segments could result in a shift of 2 to 3 cm. Although the sockets were harnessed tightly around the individual, his skin was able to shift under the electrode mounts, creating inadvertent signals at times or completely shifting his tissue away from the targeted electrode. To address this problem, a custom silicone pad was created to house the electrodes (Figure 5). It provided a focused area over the reinnervated muscle sites with increased friction to hold the skin and electrodes in place. For the most part, this proved effective in maintaining contact of electrode to skin. One exception was when the patient would sweat profusely. This perspiration created a slick surface under the silicone patch, enabling the patch to slide. In addition, during early training, some inadvertent myoelectric signals were achieved when he attempted to use the body-powered prosthesis. These challenges proved insignificant compared with the shifting of the skin and were eliminated by the wearer with additional practice.

The original plan for control of the wrist rotation was to use an FSR anterior to the shoulder for pronation and a second FSR posterior to the acromion for supination. This would allow the patient to operate all three motors simultaneously. However, during the initial test socket fitting, the subject was allowed to use the hand myoelectric signals to sequentially control wrist rotation and hand function. He was so comfortable with his new myoelectric control that he preferred this method. Two options for switching between

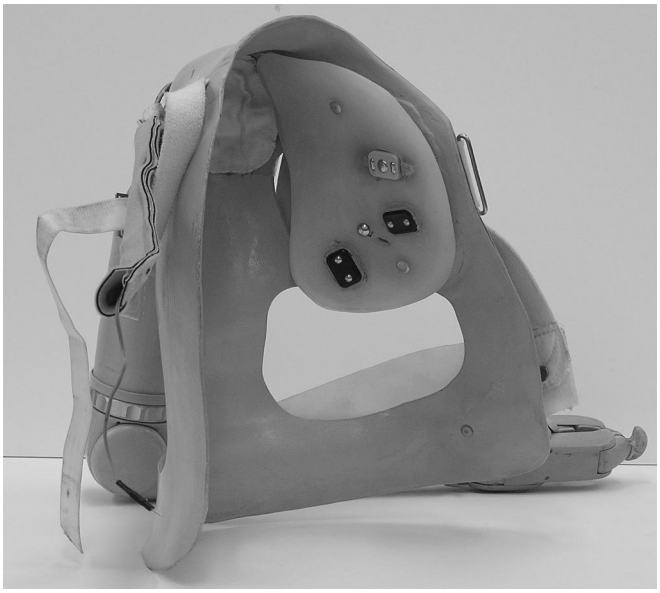

Figure 5. Custom silicone pad that secured electrodes.

hand and wrist function were tried; a co-contraction of the hand control muscles or contact with the FSR posterior to the acromion could change modes between the hand and wrist. Both controls were ultimately left in the design; however, the posterior FSR proved to be his preferential means of mode selection.

The left prosthesis also had an electronic lock/unlock added to the shoulder, which, as the right, was operated by an FSR mounted superior to the glenoid region. Both were activated by shoulder elevation.

FUNCTIONAL OUTCOME

After the fittings and training were completed, several tests were performed with both the old and new prostheses. For greater detail see Kuiken et al.[7] With a standardized box and block test,[9] the subject was 2.5 times faster with his experimental nerve-transfer prosthesis compared with his conventional device. A clothes pin test was developed in which the patient moved clothes pins from a horizontal bar up to a vertical bar (and thus had to use his elbow, wrist, and terminal device). On this test, he was 26% faster. In addition to speed, the quality of movement improved. Operation of the prosthesis was noticeably smoother. He could operate both his elbow and terminal device simultaneously and thus was able to throw a ball. In addition, the subjective feedback by the patient proved to be of greater significance. He preferred the myoelectric design because he felt that he could perform tasks more easily and quickly. He also could perform additional tasks with the new setup (including opening small jars, using scissors, and shaving) that he could not perform with the older design. He reported the device was much easier to use. Perhaps his most descriptive statement was "Now I don't have to think about it so much—I just do it."

DISCUSSION

We describe the first application of targeted reinnervation for improved myoelectric prosthesis control. By transferring the residual peripheral nerves to the pectoralis muscles of this patient, four new independent myoelectric control sites were made. These new sites allowed the patient to simultaneously control his terminal device and elbow. Subjectively, the control felt more natural and easier for this patient. This was expected because the residual nerves were enabled so they could control functions in the prosthesis that they had previously controlled in the patient's arm before amputation. Objective testing demonstrated that the patient could simultaneously control both his terminal device and elbow at the same time with just myoelectric signals. He was considerably faster in simple tests using his powered terminal device, wrist, and elbow.

This first case demonstrates the potential of targeted reinnervation. Viable nerves can be transferred to viable "spare" muscle and they will reinnervate the muscle. Muscle essentially serves as a biological amplifier of the nerve signal. Targeted reinnervation has the potential to be applied to various levels of amputation. High upper limb amputations, shoulder disarticulation, and transhumeral amputations are the most obvious and where the functional deficit is greatest. This technique has the potential to be used with transradial amputation for the control of a thumb in a multifunctional hand. Target reinnervation may someday prove useful for transfemoral amputees for control of powered knees and ankles when these devices become practical.

There are many challenges in the application of targeted reinnervation. First, the reinnervation process is slow; it took about 6 months before the pectoral muscle was well reinnervated and the experimental control of the prosthesis could be applied. Currently there is nothing that can be done to speed this process, so an intermediate prosthesis is required. Fitting the experimental prosthesis presented several challenges. One of the most difficult technical challenges in this patient was keeping the surface electrodes over the reinnervated muscle segments. The muscle segments had no insertion or fixed distal attachment, so the muscle and skin retracted when the subject contracted these muscle segments. In future procedures, this problem can perhaps be minimized by surgically fixing the distal end of the muscle segments to underlying fascia or bone. Furthermore, it may be possible to develop better electrode attachment systems.

Another challenge was the subject's ECG signal interfering with his myoelectric signals. This necessitated setting the myoelectric thresholds higher than would be desired and narrowed the operational window. This ECG interference contributed to the radial nerve transfer not being used. Effectively filtering out the ECG signal in shoulder disarticulation fittings will be needed for more robust control systems.

Although targeted reinnervation shows exciting potential, much more research is needed. Refinement of the surgical technique is desired. A functional ulnar nerve transfer (which

we failed to achieve) might allow for control of an additional degree of freedom, such as wrist flexion. Improved electrode interfaces or even intramuscular EMG recording systems could provide a more stable recording platform and possibly record more control information.[10,11] Signal processing algorithms are needed to filter out the ECG. The potential signal content in the reinnervated muscle segments is high; they may contain information from all of the amputated muscles. Advanced signal processing techniques may allow for a more robust control system or the control of more degrees of freedom.[12–21]

Targeted reinnervation and other current research on the control of upper limb prostheses hold the promise to improve the operation of artificial arms. Improved control will allow the control of more agile and complicated devices. There is now a greater need to develop powered shoulders, humeral rotators, two or three degree-of-freedom wrists, and multifunction hands. Such devices, coupled with more intuitive and robust control systems, could greatly increase the function of prostheses and the quality of life for people with limb loss.

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