

# A Novel Targeted Sensory Reinnervation Method to Enhance Feedback and Improve Function of Myoelectric Prostheses after Upper Limb Amputation

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## Abstract

Traumatic amputation of the arm results in devastating consequences. In comparison to body powered prosthesis, myoelectric prostheses offer a number of advantages including natural control using a patient's own muscle signals to operate the device. However, even with improved motor control, the lack of sensory feedback from the prosthetic hand remains a formidable barrier that severely limits the use of the prosthesis for fine dexterous tasks. In this study, we set out to investigate the feasibility of a new surgical procedure for transhumeral amputees that would allow the regenerating sensory nerve fibres from the median and ulnar nerves to reach the target sensory receptors some distance away from the reinnervated muscle in a shorter amount of time. We started with cadaver dissections to investigate the feasibility of different re-routing options of sensory nerves to target cutaneous nerves in the residual limb. We used the information gained from the anatomic study as a roadmap and applied the procedure on a patient with transhumeral amputation. We then studied the sensory outcomes by applying a sensory feedback device to connect the terminal device of a robotic myoelectric training tool to the area of reinnervated skin for digital sensory feedback during a functional task. In addition to being able to learn to control the robotic arm quickly, the subject could perform a grab and release task relying entirely on cutaneous sensory feedback without visual guidance. We believe that this new sensory reinnervation approach could bridge an important missing link to enhance the control of myoelectric prosthesis.

## Introduction

Traumatic amputation of the arm results in devastating consequences. Those afflicted are often young individuals in their productive years of life. The need for multifunctional articulated hands and less reliance of visual attention when using a prosthesis rank the highest in priority to improve acceptance and usage of the prosthetic device.<sup>1</sup> Body powered prosthesis using cables and harnesses to operate a hook have been around since the American civil war. Unfortunately, the function of those prostheses falls far below that of the natural human arm. In comparison, myoelectric prostheses offer a number of advantages including natural control using a patient's own muscle signals to operate the device. With advancements in design of new multiarticular prosthetic limbs with multiple grip patterns and degrees of freedom, the motor capacity of prosthetic limbs is advancing quickly. Targeted motor reinnervation is currently the most viable option to increase the number of inputs for myoelectric control.<sup>2</sup> However, even with improved motor control, the lack of sensory feedback from the prosthetic hand remains a formidable barrier that severely limits the use of the prosthesis for fine dexterous tasks.

## Materials and Methods

In this study, we set out to investigate the feasibility of a new surgical procedure for transhumeral amputees that would allow the regenerating sensory nerve fibres from the median and ulnar nerves to reach the target sensory receptors some distance away from the reinnervated muscle in a shorter amount of time. We started with cadaver dissections to investigate the feasibility of different re-routing options of sensory nerves to target cutaneous nerves in the residual limb. On a fresh cadaver, we identified the cutaneous nerves in the upper arm. These included the medial brachial cutaneous, intercostobrachial cutaneous (T2), posterior brachial cutaneous and the cutaneous branch of the axillary nerve. Their skin entry locations and distance to the biceps and triceps muscles were measured.

Using the information from the cadaver dissections as an anatomic

map, we executed the novel targeted sensory reinnervation approach on a 20 year old subject with transhumeral amputation. To ensure that the fascicles chosen for sensory reinnervation had a high sensory nerve fibre content, somatosensory evoked potential (SSEP) on individual fascicles was done. In addition to the standard targeted motor reinnervation as previously described<sup>3,21</sup>, we were able to isolate several fascicles of the median and ulnar nerve through intrafascicular dissection. In the case of the median nerve, the fascicle showing the largest SSEP was then transected at the distal end and directly coapted to the end of the intercostobrachial cutaneous nerve (T2) close to its entry to the skin. The same procedure was done on the ulnar nerve and one of its fascicles was coapted to the cutaneous branch of the axillary nerve.

## Results

To test the utility of the targeted sensory reinnervation procedure, the subject was asked to perform a gripping task at the robotic laboratory 6 months after surgery using a myoelectric training tool (MTT). The MTT includes a robotic arm with a gripper that mimics the hand open/close movements of commercial prostheses. The gripper is controlled by linearly mapping the EMG signals generated by the reinnervated biceps and triceps muscles in the upper arm to the angular velocity of the gripper motor. A force sensitive resistor (FSR) was bonded to the tip of the gripping device in order to measure grip pressure. A servomotor with a tactor was secured to the skin in the intercostobrachial cutaneous nerve territory that carried sensation of the tip of the index finger. The voltage output of the FSR was linked to the movement of the tactor via a non-linear mapping with an emphasis on increased sensitivity for lighter pressures. The robotic gripping device was capable of exerting up to 4 N of force.

Once blindfolded to remove any visual cue, the subject was asked to grip a rubber ball guided by only sensory feedback on his upper arm that carried sensation of the index finger. He was asked to indicate when he could feel the gripping device had just come into contact with the rubber ball, and when the ball was gripped tightly. Still blind folded, he was then asked to release the ball slowly, again to indicate

when he could feel the ball about to slip and when he felt the ball actually drop. The test was captured by 2 video cameras for offline kinematic analysis. Timing of the subject's response on various points of contact with the rubber ball was calculated and the results were averaged over 3 trials.

During each trial, the patient was blindfolded while trying to grab and relax a rubber ball using the myoelectric training tool. To close the robotic gripper on the ball, the patient had to volitionally contract the portion of the biceps muscle reinnervated by the median nerve. As the gripper made initial contact with and finally firmly grasped the rubber ball, the subject was able to perceive those events through graded tactor feedback linked to the FSR. After the gripper reached its maximum closing pressure, the subject was asked to slowly release the rubber ball by contracting the reinnervated triceps muscle. During that task, he was able to sense when the ball began to slip, and when it had dropped (shown in the video supplementary file). Using the kinematic data averaged over 3 trials, the subject was able to sense that the ball had dropped within  $440 \pm 490$  ms (mean  $\pm$  sd). Of these, time for the first trial was particularly prolonged, as the task was brand new to the subject. If the preliminary warm up trial was excluded, the time delay was only  $170 \pm 94$  ms.

## Discussions

In this study, we demonstrated the feasibility of establishing a sensory map of the hand through transferring fascicles from the median and ulnar nerves to the cutaneous nerves on the amputated residual limb. This made a functional difference as the subject was able to utilize this sensory feedback to execute fine motor tasks on a myoelectric training tool without having to rely on visual guidance. Since those tests were carried out at a very early stage before sensory reinnervation was complete, we anticipate that the functional effects will likely be even more striking as the reinnervation process becomes more advanced.

The need to enhance sensory feedback from prosthetic devices to the user is an issue of prime importance when trying to restore natural intuitive control following upper limb amputation. Attempts to use sensory substitutions have been tried in the past but have not become widely used or accepted, likely due to the non-physiological nature of the feedback. The ability to restore physiological appropriate touch feedback to the amputee in a way that they "feel" their prosthetic fingers contacting and gripping an object in a natural manner would be a major advancement in prosthetic replacement.

Following amputation, the sensory nerves that used to carry signals from the hand to the sensory cortex for interpretation of touch, pressure, heat, and position sense are still present, but they are disconnected from their end organs in the residual limb. Our approach was to specifically target these sensory nerves and directly reconnect them with functioning cutaneous sensory end organs in order to restore the lost "hand map" to a new area of skin. However, there are several known barriers to sensory reinnervation that must be overcome. Sensory end organs become atrophic and generally degenerate after denervation.<sup>4</sup> To preserve sensibility to different sensory modalities, it is important to minimize the time of denervation following nerve coaptation. A second important consideration when trying to preserve the function of a wide range of sensory end organs is the presence of a contiguous conduit. The potential advantages of the proposed technique of targeted sensory reinnervation is that with the end to end coaptation, the crushed or damaged portion of the nerves are first cut back to healthy fascicles in the amputated medial and ulnar nerve trunks. Then, specific sensory fascicles are isolated in a time efficient manner intra-operatively, so they can be selectively reinnervated

without compromising reinnervation of motor fascicles to the motor nerve terminals. The sensory fascicles are then directed to an intact sensory cutaneous nerve that has been freshly sectioned, so that there has been no time for sensory end organ atrophy and degeneration. The new coaptation is also done as closely to the new cutaneous nerve skin entry point as possible, to allow the shortest route and shortest time for reinnervation.

In previous studies of subjects undergoing the TMR procedure without the directed sensory treatment, it is thought that sensory end organs become reinnervated by growing through muscle bellies to the overlying denervated skin. Therefore, the sensory reinnervation that is seen with TMR tends to occur right overtop the muscle sites, which can lead to difficulties when trying to implement all of the necessary hardware into the socket, including pickup electrodes and sensory feedback tactors, in the same area. This "real estate" problem can potentially be avoided with our method, as the cutaneous fascicles can be directed to cutaneous territories distant from the expected muscle electrode sights.

Another potential advantage of using a specific cutaneous nerve is that the dermatomal territory of that nerve may remain intact, and the reinnervating median or ulnar nerve has the potential to reinnervate the entire territory of the cutaneous nerve. This defined cutaneous territory versus random territory due to terminal denervation of skin and subcutaneous tissue could have an advantage in spreading out the recovering sensory map over a wider area, with potentially less overlap of digits.

Further research needs to focus on comparing the outcomes and sensitivity of the directed sensory approach presented here, to the traditional TMR approach and determining if the discrimination and modalities restored are substantially different. Also, a similar targeted sensory approach should be explored for shoulder disarticulation amputation as there is potential to use trunk sensory branches for the cutaneous reinnervation. Finally, there is an ongoing need to go beyond a "proof of concept" within the laboratory, to socket integration trials in a functional environment to determine if sensory feedback leads to improvement in overall prosthetic performance and patient usage and acceptance.

## Conclusions

Sensory feedback reminds an important missing link in prosthetic control. The novel targeted sensory reinnervation presented in this work has the potential of bridging that gap and to improve the functional outcomes.

## References

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## **Acknowledgements**

Fundings for this study was provided by the Canadian Institute of Health Research. We would like to thank Joshua Wong, Tan Lin, Jerome Satkunam and Michael Stobbe for their assistance.