CREATING PRESSURE AND THERMAL TACTILE SENSATIONS IN THE PHANTOM HAND USING NON-INVASIVE STIMULATION

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ABSTRACT

Invasive peripheral nerve interfaces have demonstrated the value of restored touch perceptions in the missing hand elicited by electrical stimulation after arm amputation. However, invasive interfaces may not be the preferred option for many prosthesis users. We explored the use of non-invasive mechanical stimulation, targeted transcutaneous electrical nerve stimulation (tTENS), and thermal stimulation of naturally occurring reinnervated nerve sites in the residual limb to restore multiple modalities of touch in the phantom hand. In two individuals with arm amputation, we reported tactile sensations of pressure, elicited by mechanical stimulation and tTENS, and cooling, elicited by thermal stimulation, in the phantom hand. Tactile perceptions and stimulation locations remained stable over multiple years. We observed that the activated regions of the phantom hand may by stimulation modality specific, in that tactile sensations did not always overlap when different stimulation modalities were used at the same location on the residual limb. These results may be useful in helping restore a broad range of touch feedback for prosthesis users through non-invasive stimulation approaches.

INTRODUCTION

Restoring the sense of touch to the missing hand after amputation can help improve prosthesis usage and function [1], [2], enhance decoding of electromyography prosthesis control signals [3], increase sensorimotor connectivity [4], and promote prosthesis integration into a user's body image [2], [5]. Invasive peripheral nerve stimulation techniques can directly excite sensory nerve fibers and elicit sensations of touch in the phantom hand [1], [2]. Non-invasive stimulation approaches have also restored touch perceptions in the missing hand after amputation.

Tactile sensations in the missing hand can be induced by mechanical stimulation of reinnervated sites in the skin of the residual limb in individuals both with [6] and without [7] targeted sensory reinnervation (TSR) surgeries. Targeted transcutaneous electrical nerve stimulation (tTENS) has also been used to restore sensations of touch in the phantom hand of individuals with arm amputation [8] and can be modulated to create pressure-related tactile sensations ranging from light touch to pain [9].

An important element of touch feedback for prosthesis users is being able to convey a useful range of tactile sensations. Perceptions from non-invasive mechanical and electrical stimulation are typically reported as being pressure, vibration, or tingling sensations in the phantom hand [3], [7]. Recently, sensations of temperature have also been restored through non-invasive thermal stimulation of reinnervated nerve sites in the skin [10], [11] and these thermal perceptions can be used to enable object identification during closed-loop prosthesis control [10].

In this study, we investigated the use of non-invasive mechanical, electrical, and thermal stimulation to elicit tactile sensations of pressure and temperature in the phantom hand of individuals with arm amputation. We quantified the resulting perception location and quality in addition to stimulation location for all three stimulation modalities.

METHODS

Two individuals with arm amputation participated in this study. Participant A1 had a left transhumeral arm amputation and participant A2 had a right transradial arm amputation. Neither participant had undergone targeted sensory reinnervation surgery (TSR); however, there were sites on the residual limb that, when stimulated, elicited

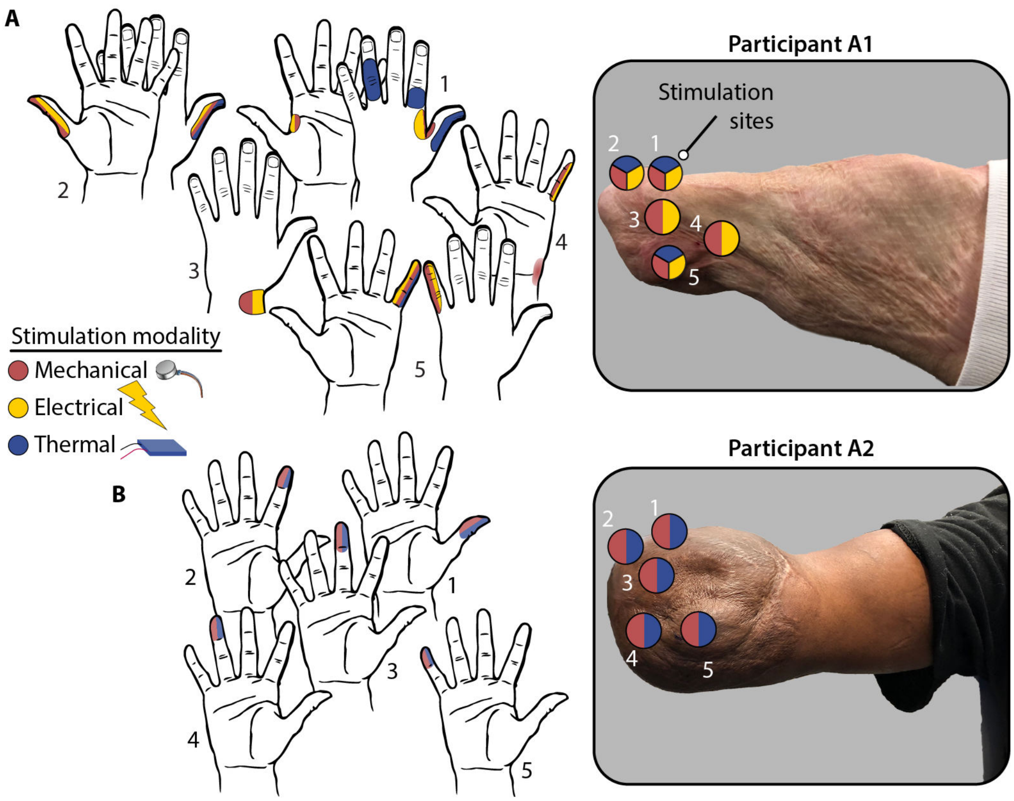

Figure 1: Tactile sensations in the phantom hand as a result of non-invasive skin stimulation. (A) Mechanical, electrical, and thermal stimulation of reinnervated nerve sites of participant A1 elicited sensations of pressure and temperature in the phantom hand. (B) Mechanical and thermal stimulation on the skin in participant A2's residual limb elicited sensations of pressure and temperature. Colors indicate stimulation modality and corresponding tactile perceptions.

sensations in the phantom hand. These sensory sites on the residual limb were identified based on prior sensory mapping studies with the participants [3], [10].

Three different stimulation modalities were used to elicit tactile sensations in the phantom hand. Mechanical stimulation was delivered through a 1 cm rounded plastic probe that was indented into the participant's skin by the experimenter. Electrical stimulation, tTENS, was delivered as a 4 mA biphasic square wave with a 0.5 ms pulse width (200 ms per phase with a 100 ms interphase interval) and a stimulation frequency of 4 Hz (DS8R, Digitimer). Thermal stimulation was delivered using a Bi_2Te_3 thermoelectric cooling (TEC) device with a surface temperature of 16 °C and an 11 mm x 11 mm surface area (Custom Thermoelectric).

Stimulation was applied to the stimulation sites on the residual limb and participants used a hand map to draw the activated regions of their phantom hand. Participants verbally reported the quality of tactile sensations from the stimulation. Participant A1 received stimulation from all three modalities (mechanical, electrical, and thermal) and participant A2 received mechanical and thermal stimulation. Participant A2 performed two follow-up sensory mapping experiments 11 and 23 months after the initial sensory mapping experiment. All experiments were approved by the Johns Hopkins Medicine Institutional Review Boards.

RESULTS & DISCUSSION

We found five unique locations on the residual limb for each participant that, when stimulated, produced tactile sensations in unique regions of the phantom hand (Figure 1). Sensations of pressure were elicited in the phantom hand by using mechanical stimulation of the reinnervated sensory sites on the residual limbs of both participants. The evoked tactile sensations from mechanical stimulation were described as being a "pressure" or "pressing" in the phantom hand.

For participant A1, tTENS also produced sensations of touch, specifically a pulsing pressure that matched the 4 Hz stimulation frequency, in the same regions of the phantom hand as did mechanical stimulation (Figure 1A). The evoked sensations from tTENS were described as being “pressure”, “pulsing”, and “tingling” in the phantom hand and tactile sensations were not perceived at stimulation site on the residual limb. Prior work suggests that the projected fields in the phantom hand from mechanical stimulation and tTENS of the same sensory site on the residual limb do not always overlap [7]; however, the projected fields for the two stimulation modalities did overlap for participant A1 (Figure 1A). Because every amputation is unique to each individual, it is reasonable that the projected fields may overlap for different stimulation modalities (e.g., mechanical and tTENS) in some individuals but not in others.

Sensations of temperature, specifically cooling, were reported in the phantom hand as a result of thermal stimulation on the residual limb from the TEC device. Three of the five stimulation sites on participant A1’s residual limb evoked cooling sensations in the phantom hand (Figure 1A) compared to all five stimulation locations on A2’s residual limb (Figure 1B). The thermal project fields did not all overlap with the mechanical and tTENS project fields for the same stimulation locations for A1. That is, one of the stimulation sites, when activated thermally, produced cooling sensations in the thumb and back of the index and ring fingers but elicited pressure sensations in between the thumb and index finger when the same location on the residual limb was activated with mechanical stimulation or tTENS (Figure 1A). The observations of non-overlapping projected fields in A1’s phantom hand based on stimulation modality align with prior results and have been reported across multiple individuals [7], [10]. For A2, thermal stimulation was perceived in the same region in the phantom hand as mechanical stimulation (Figure 1B). These sensory regions in the phantom hand remained stable over the two years of testing in that the stimulation locations on the residual limb and the corresponding regions of tactile activation in the phantom hand did not substantially change.

These results demonstrate that non-invasive stimulation can be used to activate underlying nerves in the residual limb and produce both pressure and thermal tactile sensations in the phantom hand after amputation. Interestingly, stimulating the same location on the residual limb with different modalities (e.g., mechanical, thermal) can produce sensations at different locations in the phantom hand.

CONCLUSION

Both pressure and thermal tactile sensations can be evoked in the phantom hand of individuals with arm amputation through the use of non-invasive stimulation of the residual limb. Having undergone TSR surgery is not a requirement to enable these tactile perceptions in the phantom hand through non-invasive stimulation of underlying sensory nerves in the residual limb. Mechanical and electrical stimulation enable sensations of pressure or pulsing in whereas thermal sensations or enabled by thermal stimulation of the sensory sites on the residual limb. The location of perceived tactile sensations in the phantom hand can be stimulation modality dependent. These results help demonstrate the possibility of restoring multiple modalities of touch to prosthesis users through non-invasive stimulation.

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