PHANTOM HAND ACTIVATION DURING PHYSICAL TOUCH AND TARGETED TRANSCUTANEOUS ELECTRICAL NERVE STIMULATION

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ABSTRACT

Restoring the sense of touch is a critical component for a closed-loop prosthetic limb. In an upper limb amputee, we explored regions on the residual limb that elicited sensory activation of the phantom hand through either physical touch or targeted transcutaneous electrical nerve stimulation (tTENS). We found that sensory sites on the residual limb responded to either physical touch or tTENS, but typically not both. Further, some regions of the phantom hand were only activated with one of the stimulation modalities, such as the thumb or wrist. Interestingly, some locations on the phantom hand could be activated with either physical touch or tTENS but at different locations on the residual limb. Our work helps highlight potential differences in perceived location of sensory feedback depending on the stimulation modality.

INTRODUCTION

Direct neural interfaces, such as the flat interface nerve electrode (FINE) [1], and advanced surgical techniques, such as targeted muscle reinnervation (TMR) [2] and targeted sensory reinnervation (TSR) [3], [4], have enabled significant advances in providing sensory feedback to upper limb amputees. The sense of touch can be restored to the phantom hand of using direct electrical nerve stimulation [5]. Recently, researchers used bioinspired stimulation models to convey perception of texture [6], mechanical pain [7], and increase naturalness of restored tactile sensations for improved functionality [8]. Restored sensation to the phantom hand can be achieved through noninvasive approaches including cutaneous vibration [3] and targeted transcutaneous electrical nerve stimulation (tTENS) [7], [9], [10]. Recently, researchers showed that you can even elicit illusory perception of phantom hand movement during cutaneous vibration after TMR [11]. In addition to continued research on prosthesis technology, such as advanced myoelectric control methods [12], [13] and tactile sensing [7], [14], [15], work on sensory feedback is progressing quickly.

We explored the regions of phantom hand activation in an amputee using both physical touch and TENS. The purpose of the sensory mapping was to identify the similarities and differences between the two sensory activation modalities. Because sensory feedback is possible through both physical (cutaneous vibration) and electrical (TENS or direct nerve stimulation) modalities, it is important to understand the differences to provide useful and meaningful sensory information to prosthesis users.

METHODS

As a case study for comparing tactile feedback modalities, the participant discussed was a 64 year old male with a left transhumeral amputee who previously underwent TMR surgery and has an osseointegrated interface for prosthesis attachment in his residual limb. The participant provided written informed consent to be a part of this study. This research protocol was reviewed and approved by the Johns Hopkins Medicine Institutional Review Boards in accordance with all applicable Federal regulations governing the protection of humans in research.

Sensory stimulation of the participant's phantom hand was achieved through either physical touch or targeted TENS. To active the phantom hand with physical touch, the participant used his intact hand to identify and palpate known

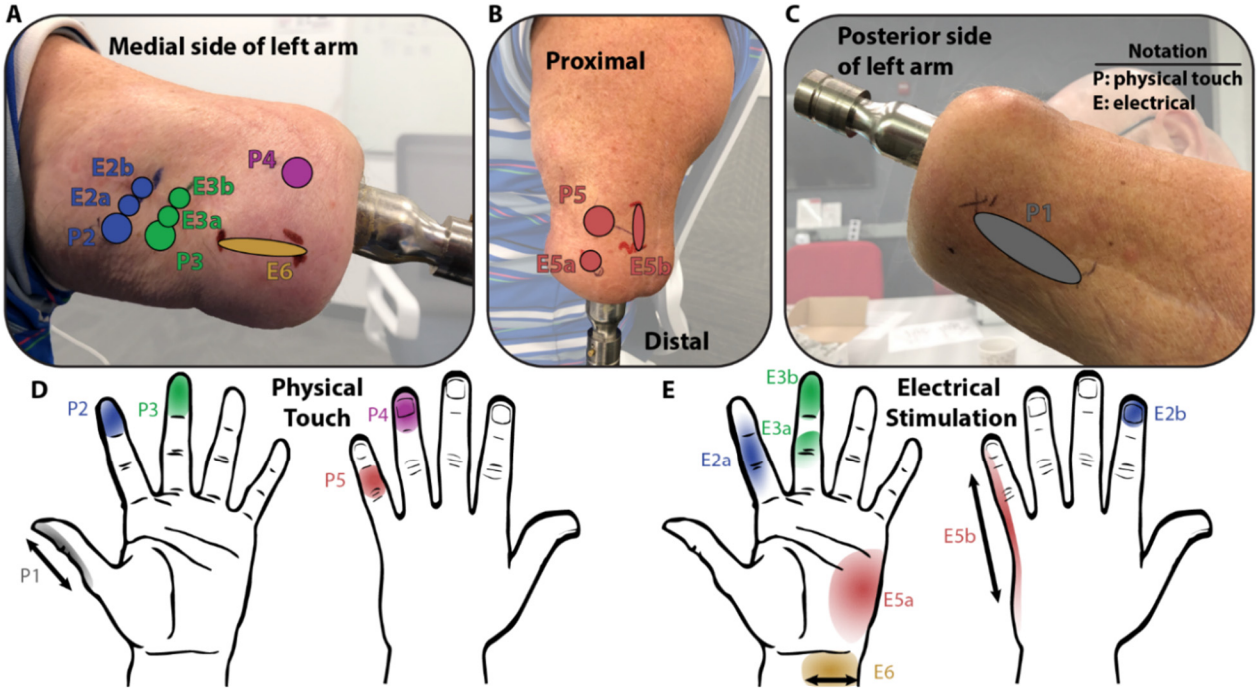

Figure 1: Phantom hand activation from physical and electrical stimulation. (A) Sensory stimulation sites on the medial portion of the arm that correspond to the index finger, middle finger, and wrist. (B) Little finger and (C) thumb sensory stimulation sites on the residual limb. Larger circles represent sites where physical touch activates the phantom hand, and the smaller circles represent sites that activate the phantom hand during tTENS. (D) Sensory activation in the phantom hand during physical touch of the corresponding sites on the residual limb. (E) Sensory activation in the phantom hand during tTENS.

regions, on the residual limb, of sensory activation in the phantom hand. Once a stimulation site on the residual limb was found, the participant used a marker to draw out the activated regions.

Targeted TENS was used to electrically activate underlying nerves in the residual limb to elicit sensory perceptions in the phantom hand. Sensory mapping was performed by scanning a 1 mm beryllium copper (BeCu) probe across the surface of the skin on the residual limb. The frequency (f) of electrical stimulation ranged from 2 – 4 Hz and the pulse width (pw) was 5 ms. The amplitude of the stimulation (I) ranged from 1.5 – 1.8 mA. We've validated the tTENS method in previous studies [7], [9] The locations that elicited sensory activation in the phantom hand were marked on the residual limb.

RESULTS

Sensory activation of the phantom hand is shown in Fig. 1. Locations on the residual limb that correspond to regions of the phantom hand are labeled in Fig. 1A-C. The sites on the residual limb that activate the phantom hand during physical touch are labeled with *P*, whereas the sites that respond to tTENS are labeled with *E*. The phantom hand activation for each stimulation site is shown in Fig. 1D-E. The participant reported that sensory stimulation was perceived like a pressure or a light touch and was localized to the phantom hand for both physical touch and tTENS.

The phantom thumb was only activated during physical touch (P1) whereas the palm and wrist were only activated during electrical stimulation (E5 and E6, respectively). The arrows next to P1 and E6 indicate that the participant could feel the physical touch (P1) or the tTENS probe (E6) moving within the sensitive region on the residual limb. The participant reported that these sensations were localized to the phantom hand.

The index and middle fingers were activated during both physical touch and tTENS. Further, the region of activation was similar for both modalities in the index finger, but differed slightly in the middle finger. For both index and middle fingers, the stimulation sites on the residual limb were different for the physical and electrical stimulations; however, they were relatively close to each other.

DISCUSSION & CONCLUSION

Based on our observations, the sites on the residual limb that are linked to activation of the phantom hand are different for physical touch and tTENS. That being said, we did observe that some of the locations, specifically for the index and middle fingers, are close in proximity. The fact that these stimulation locations are close could be indicative of the underlying sensory nerve fibers that respond to TENS being

along the same nerve fascicle with fibers that innervate the skin at locations where physical touch elicits sensory activation in the phantom hand.

We believe that the physical touch sites on the residual limb are likely areas of the skin where sensory nerve fibers reinnervated superficially and thus produce action potentials as a result of physical manipulation. The underlying nerves in regions activated by tTENS are likely deeper in the soft tissue and are activated by the electrical pulses. It is reasonable to consider the possibility that the physical touch activation sites contain nerves reinnervated into the skin, and tTENS responsive sites are regions where nerve fibers or fascicles are close enough to the surface of the skin to allow electrical activation of the fiber or fascicle. The mechanical manipulation at reinnervated sites or where nerve fibers terminate likely causes the perceived sensation in the phantom hand. The tTENS sites on the residual limb are likely regions where electrical stimulation penetrates along the path of a fiber, eliciting the phantom sensory activation.

Because of the different mechanism of nerve activation (mechanical manipulation of reinnervated nerves and electrical stimulation of underlying nerve fibers or fascicles), it might explain why we didn't observe physical touch and tTENS sites being at exactly the same location on the residual limb. The force exerted on the skin by the TENS probe was likely not large enough to elicit mechanical activation of the reinnervated sites on the residual limb that corresponded to sensory activation of the phantom hand during touch.

Some regions, like the thumb and wrist are only activated by either physical touch or tTENS, respectively. The thumb responding to physical touch but not tTENS could be due to the underlying nerve fibers or fascicle innervating that location being too deep for the electrical stimulation to reach it. Similarly, the region of tTENS wrist activation could have an underlying nerve fascicle that is superficial enough to be activated by electrical stimulation, but the reinnervation occurs deeper in the soft tissue, thus preventing mechanical stimulation on the surface of the skin.

Every amputation case is different and each participant requires thorough sensory mapping to understand the perceived sensations in the phantom hand due to physical and electrical stimulation. Although we previously explored tTENS in multiple subjects [7], [9], every sensory map is different and varies between participants. As closed-loop prosthesis research continues to advance, it is important to explore and quantify the various forms of sensory stimulation modalities and resulting perceptions in amputees.

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