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BIOMEDICAL ENGINEERING

Ph.D. Dissertation Defense

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"Multisensory integration of lower-limb somatosensory neuroprostheses: from psychophysics to functionality"

by

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ABSTRACT:

Over one million individuals in the United States alone have a lower-limb amputation. Though locomotion is a sensorimotor process, no commercially available prostheses offer somatosensory feedback, and lower-limb amputees continue to face locomotor challenges as a result. Prior work has shown that integrating sensory feedback into a prosthesis can improve functional ability, reduce phantom pain, and enhance prosthesis embodiment. Until recently, sensory feedback was primarily restricted to vibration or electrocutaneous stimulation, neither of which isolates and activates afferent sensory fibers that refer to the missing limb. Recent studies have demonstrated that electrically stimulating the residual nerves of amputees can elicit somatosensory percepts referred to the missing limb.

Though peripheral nerve stimulation (PNS) takes advantage of the existing neural pathways that carry sensory information from the amputated limb to the brain, neural stimulation does not activate these afferent fibers in the exact same manner as physically-applied tactile stimuli. We originally hypothesized that these differences in neural activation may cause PNS-evoked sensation to be perceived differently than natural touch with respect to temporal synchrony (Aim 1) and multisensory integration (Aim 2). In Aim 1, we found that the processing time and temporal sensitivity for PNS-evoked somatosensation were not significantly different than natural tactile sensation. The similarity in visuotactile temporal synchrony provided further evidence that PNS-evoked sensations are processed in broadly the same way as natural touch. In Aim 2, we established that much like natural somatosensation, visual inputs and postural manipulations could reinforce PNS-evoked somatosensory percepts. In intact sensory systems, multiple senses interact to maximize perception. This interaction had not been previously demonstrated and it is important for sensory neuroprostheses, which will be used in diverse environments with various sensory resources available.

The findings from Aims 1 and 2 demonstrated that PNS-evoked sensation has similar properties to natural somatosensation, but they did not guarantee that the body would utilize the sensory information accordingly. In Aim 3, we showed that amputees utilized PNS-evoked plantar sensation while performing a challenging locomotor task, which revealed a significant and immediate benefit of somatosensory feedback to lower-limb amputees. The use of a sensory-enabled prosthesis did not change the amputees' locomotor strategies, which indicated that longer-term therapeutic benefits might require a longer familiarization period with the device, or even a prescribed training regime.

This was one of the first studies in which lower-limb amputees were able to perceive somatosensory percepts referred to their missing feet. The PNS approach allowed us to decouple sensory stimuli in a way that is not ordinarily possible, thus providing an unprecedented opportunity to probe the underlying characteristics of human multisensory integration. Aims 1 and 2 represent original contributions to understanding the temporal perceptual properties and multisensory integration of PNS-evoked sensation in comparison to natural tactile sensation. Prior to the study in Aim 2, the effect of posture manipulations on tactile localization had received little attention with respect to locomotion, even in able-bodied individuals. Finally, the role of cutaneous plantar sensation in ambulatory searching tasks was largely unexplored before the study conducted in Aim 3. The knowledge gained in this dissertation lays the groundwork for future studies with additional populations and anatomical targets. Both trans-femoral and bilateral amputees are missing more sensory resources than unilateral trans-tibial amputees, and could benefit substantially from adding balance resources, such as somatosensation, back into their postural reserve.