Bidirectional Intracortical Interfaces for Prosthetic Limb Control

Robert A. Gaunt[1-3], Jennifer L. Collinger[1-4], Sharlene N. Flesher[5], Chris L. Hughes[2,3], Angelica Herrera[2,3], Jeff Weiss[1], John Downey[6], Andy Schwartz[3,7], Michael L. Boninger[1,2,4]

[1]Department of Physical Medicine and Rehabilitation, University of Pittsburgh, PA, USA
[2]Department of Bioengineering, University of Pittsburgh, PA, USA
[3]Center for the Neural Basis of Cognition, Pittsburgh, PA, USA
[4]Department of Veterans Affairs, Pittsburgh, PA, USA
[5]Department of Neurosurgery, Stanford University, Stanford, CA, USA
[6]Department of Organismal Biology, University of Chicago, Chicago, PA, USA
[7]Department of Neurobiology, University of Pittsburgh, PA, USA

Abstract — Intracortical microelectrode arrays can be used to record the activity of populations of neurons in the brain as well as directly modulate their activity through microstimulation. To create a prosthetic system that restores the full capacity of a healthy limb—one that is capable of both controlling a limb and enabling a user to feel sensations from the prosthesis—we implanted microelectrode arrays into the primary motor and somatosensory cortices. Recordings from populations of single neurons in motor cortex enabled a person with spinal cord injury to control up to seven simultaneous degrees-of-freedom in the prosthetic arm, enabling him to grasp, transport and manipulate a variety of objects in his workspace. Microstimulation in the somatosensory cortex evoked perception of different features of tactile sensations even after long-term spinal cord injury. These evoked percepts have a range of qualities from pressure and touch, to tingling and buzzing. We have also found that different stimulus frequencies elicit sensations with different perceptual qualities. Further, in some functional tasks, closed-loop stimulation improves task performance. These findings offer proof-of-concept that sophisticated, closed-loop prosthesis control can be achieved through a direct brain interface in people with long-term spinal cord injury.

Introduction

There has long been a desire to restore movement to those who have lost it, following spinal cord injury or amputation, through the creation of advanced technologies including robotic prosthetics and functional electrical stimulation systems that activate paralyzed muscle. However, as these devices have been developed, the lack of suitable control methods has become a performance bottleneck. Leveraging neuroscientific understanding of some of the mechanisms by which populations of neurons in the motor cortex lead to limb movement, it became possible to consider that real-time recording from populations of neurons could be used to control a prosthetic limb. One of the first functional demonstrations of this idea was when a non-human primate learned to control a simple prosthetic limb to feed itself [1]. Since this time, there has been rapid progress in the field, including multiple groups implanting microelectrode arrays into the motor cortex of human study participants with spinal cord injuries and other injuries or diseases that result in paralysis [2]-[7]. In current investigations, people with intracortical brain-computer interfaces are capable of controlling robotic limbs with many degrees of freedom [5]. A natural extension of this work is restoring cutaneous feedback from the hand, as sensation plays an important role in our natural ability to interact with objects. We have demonstrated that intracortical microstimulation (ICMS) in the somatosensory cortex of a person with long-term spinal cord injury can elicit sensations that feel like they originate from their own hand and have a number of different perceptual qualities including touch, pressure, tingle and buzzing [8]. We believe that more naturalistic percepts will be more easily interpreted and, as such, may be more useful in behavioral contexts. We are therefore interested in exploring how different stimulation parameters affect perception and how stimulation may be used to improve performance during functional tasks.

Methods

A 28-year-old man with a C5-C6 spinal cord injury was implanted with microelectrode arrays, including two 88-channel devices in primary motor cortex and two 32-channel devices in somatosensory cortex. This study was performed under an Investigational Device Exemption from the United States Food and Drug Administration and approved by the Institutional Review Boards at the University of Pittsburgh and the Space and Naval Warfare Systems Center Pacific. ICMS pulses were delivered through individual microelectrodes at a fixed stimulation amplitude of 60 µA (charge-balanced, 200 µs cathodic phase) to investigate the effects of stimulus parameters on perception. Pulse trains were delivered for 1 s at frequencies ranging from 20 to 300 Hz and the participant was asked to rate the intensity of each stimulus on a self-selected numeric scale that was proportional to the perceived intensity. We also measured the detection thresholds on individual electrodes using a two-alternative forced choice task. To decode movement control signals, neural spiking activity was recorded from the arrays in motor cortex using threshold crossings, binned in 20 ms intervals and smoothed using a low-pass filter with a 440 ms time constant. An endpoint velocity decoder was trained using an observation paradigm in which the participant imagined moving along with a series of virtual prosthesis movements presented on a monitor. During closed-loop stimulation trials, the participant used a prosthetic limb to pick up objects and move them from one location in the workspace to another. In this task, stimulation intensity was graded based on the magnitude of the data coming from sensors located on the hand of the robotic prosthesis.

Results and Discussion

Stimulation detection thresholds have been stable or decreasing over the course of this study and the location of the evoked percepts has remained stable. We have also found that as stimulus frequency was increased, the perceived intensity changed in ways that were dependent upon the electrode being stimulated. Some electrodes elicited the most intense percepts at the highest stimulus frequency, while other electrodes elicited the most intense percept at low frequencies, and yet others were most intense at intermediate frequencies. We also found that "low-frequency" electrodes could elicit "tapping" sensations while "high-frequency" electrodes never did. Still other percepts, described by the participant as "pin-pointy" or "tingle" were more commonly elicited by electrodes with a "high-frequency" preference. These results suggest that changing the stimulus frequency may be an effective way to modulate perceptual quality. In the functional tasks, we found that the addition of stimulation results in subtle, but important improvements in performance. Overall, trials are completed faster when stimulation is included as fewer object grasp attempts were required when stimulation was provided.

While significant work remains to develop a clinically translatable product with the day-to-day reliability that users would expect, we believe that these results clearly show the potential of this approach to restore motor control capabilities to the people that need them.

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