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Intracortical microstimulation of somatosensory cortex enables object identification through perceived sensations

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Abstract— **Advances in brain-machine interfaces have helped restore function and independence for individuals with sensorimotor deficits; however, providing efficient and effective sensory feedback remains challenging. Intracortical microstimulation (ICMS) of sensorimotor brain regions is a promising technique for providing bioinspired sensory feedback. In a human participant with chronically-implanted microelectrode arrays, we provided ICMS to the primary somatosensory cortex to generate tactile percepts in his hand. In a 3-choice object identification task, the participant identified virtual objects using tactile sensory feedback and no visual information. We evaluated three different stimulation paradigms, each with a different weighting of the grip force and its derivative, to explore the potential benefits of a more bioinspired stimulation strategy. In all paradigms, the participant's ability to identify the objects was above-chance, with object identification accuracy reaching 80% correct when using only sustained grip force feedback and 76.7% when using equal weighting of both sustained grip force and its derivative. These results demonstrate that bioinspired ICMS can provide sensory feedback that is functionally beneficial in sensorimotor tasks. Designing more efficient stimulation paradigms is important because it will allow us to 1) provide safer stimulation delivery methods that reduce overall injected charge without sacrificing function and 2) more effectively transmit sensory information to promote intuitive integration and usage by the human body.**

I. Introduction

The restoration of tactile sensation remains a critical gap as we seek to restore independence to individuals with spinal cord injury and deficits in sensorimotor function. Intracortical microstimulation (ICMS) has been a promising technology for delivering sensory feedback directly to cortex through a brain-machine interface (BMI). ICMS of somatosensory cortex creates tactile percepts in non-human primates [1], [2] and humans [3]–[6] that can be reliably perceived, localized, and discriminated by their amplitude or frequency [1]–[3]. Delivery of ICMS during motor control behaviors has been shown to improve task performance [7].

One big hurdle to restoring sensorimotor function is the design of optimal stimulation strategies that provide relevant and efficient sensory information in an intuitive way. Biological responses to tactile sensory input exhibit rapidly adapting and slowly adapting characteristics in both peripheral nerves [8], [9] and cortex [10], suggesting that a constant amplitude stimulation paradigm is not ideal. The parameter space of stimulation encoding models is large – changing amplitude, pulse width, and frequency can influence evoked percepts in both peripheral stimulation [11], [12] and ICMS [3]–[6].

Work in sensory restoration for individuals with limb amputation has shown that sensation is important [13] and that biomimetic stimulation patterns of the nerves, leveraging rapidly and slowly adapting neural responses, could be a beneficial approach for providing intuitive and functional sensory feedback [12], [14]–[16].

Beyond safety considerations (e.g., limiting total current delivered to neural tissue), studies of tactile stimulus representations in peripheral nerve [8] and cortex [10] would suggest that both rapidly and slowly adapting encoding schemes are present throughout the somatosensory neuraxis. To understand how artificial spatiotemporal sensations are utilized, we delivered ICMS feedback to a human participant while a virtual prosthetic hand grasped objects of parametrically varying shapes. Using three different stimulation paradigms, ICMS feedback varied in its temporal properties—proportional with either the sustained or transient component of the grasp force. For all stimulation methods, the participant was able to identify the different objects with above-chance performance.

II. Methods

A. Human Participant

A male participant with spinal cord injury (C5/C6 ASIA Impairment Scale Grade B) was implanted with six microelectrode arrays (Blackrock Microsystems) in sensorimotor regions in both hemispheres of his brain [5], [17], [18]. In the left hemisphere, two recording arrays and two stimulating

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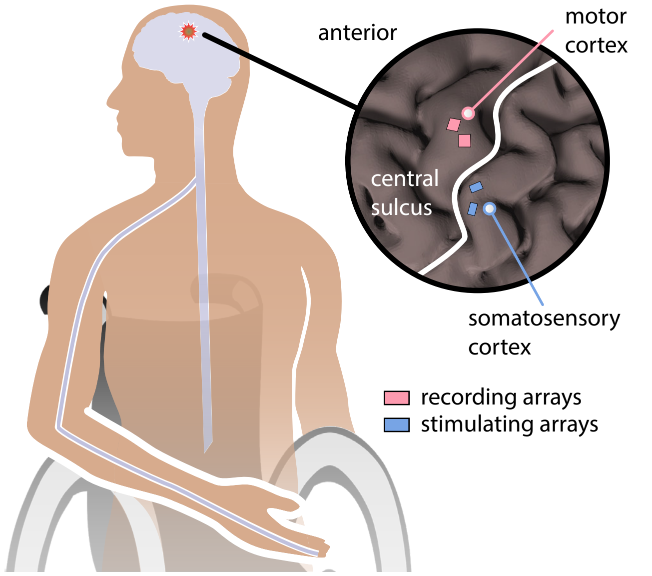

Fig. 1. Microelectrode arrays were implanted in the primary motor and somatosensory cortex of each hemisphere in the brain of an individual with spinal cord injury. We provided intracortical microstimulation to the somatosensory cortex in the left hemisphere, which created tactile perceptions in the right hand [5], to see if artificial cutaneous sensations can be used to identify objects.

arrays were place in the primary motor and somatosensory cortices, respectively (Fig. 1). Stimulating arrays each contained 32-ch (4 mm x 2.5 mm). This work was approved under Investigational Device Exemption (170010) by the Food and Drug Administration (FDA) for the purpose of evaluating bilateral sensory and motor capabilities of microelectrode array implants. The study protocol is registered as a clinical trial (NCT03161067) and was approved by the FDA, the Johns Hopkins Institutional Review Board, and the U.S. Army Medical Research and Development Command Human Research Protection Office.

The participant previously underwent extensive mapping of cutaneous sensory perceptions during ICMS [5]. Tactile sensory percepts were elicited in both left and right hands as a result of stimulating regions of the primary somatosensory cortices in the right and left hemispheres of the brain, respectively [5]. ICMS detection thresholds were in the approximate range of 10–25 μA [5] and stimulation was delivered at 100 Hz using a Cerestim R96 (Blackrock Microsystems) where each stimulation pulse is a balanced, cathodic-first 500 μs charge (200 μs per phase with interphase delay of 100 μs). For this experiment, stimulating electrodes were chosen to generate cutaneous sensations, primarily described as a pressure, in the thumb, index, middle, and ring finger regions of the right hand (Fig. 2A).

B. Experiment

The goals of the task were to 1) demonstrate the ability to identify different objects based entirely on spatiotemporal information from artificial tactile feedback through ICMS and 2) evaluate the effectiveness of using stimulation patterns based on different weightings of the sustained and transient components of grip force during object grasping.

A virtual Modular Prosthetic Limb (vMPL) scenario was used to automatically (i.e., the participant did not control it) grasp an object (Fig. 2B). The vMPL is based on the physical version of the prosthesis [19], [20] and contains force sensors in the fingertips. Three different cylindrical virtual objects were designed with varying shape. Object 1 is a uniform cylinder, object 2 is a positive sloping (from index to the little finger) cylinder with 4 segments of equal width but with a 30% scaling change in height at each segment. Object 3 is a negative sloping (from index to the little finger) cylinder with the same scaling of width and height as object 2 (Fig. 2C). The objects were designed so that each segment would align with a different finger on the vMPL during contact. The goal was to generate distinct spatiotemporal force profiles that could be used for identifying the different objects through artificial cutaneous sensations. During each grasping motion, the vMPL would close for a period of 2 s, make contact with the object for 3 s, and then open and return to the starting position over a 2 s period. The participant underwent a training period for up to 10 min where he could see the vMPL grasping the different objects while perceiving the sensory stimulation in his hand. He used this period to get familiar with the spatiotemporal cutaneous sensations produced by each object. For the experiment, the participant could not see the vMPL or the objects (no visual information) and he verbally indicated the object he perceived on each trial. Each object was randomly presented up to 15 times in each stimulation paradigm.

C. Stimulation Paradigms

To evaluate the effect of biomimetic-inspired patterns, we designed three cortical stimulation paradigms to systematically vary the weighting of the sustained (F_s) and transient (F_t) components of the force signal from the vMPL. The ICMS amplitude, I, for each finger region is determined by the combined weighting of F_s and F_t from the corresponding virtual prosthetic finger:

$$I = \beta F_s + \gamma F_t \tag{1}$$

where β and γ are weighting parameters of the sustained and transient force components (Fig. 2D).

The output of each virtual force sensor (i.e., sustained loading) was linearly mapped to ICMS amplitude with a maximum stimulation current of 80 μA to each finger region. Safety limitations prevented the total stimulation, summed across all stimulated finger regions, from exceeding 720 μA (144 nC/phase). The transient component of the force profile, which was also mapped to the ICMS amplitude for each finger region, was calculated by numerical differentiation of the force signal over an approximately 20 ms window. The three stimulation paradigms varied in the relative contribution of the sustained and transient force components to the ICMS amplitude. Stimulation paradigm 1 utilized only the sustained loading profile ($\beta = 1, \gamma = 0$), paradigm 2 equally weighted the sustained and transient force components ($\beta = 0.5, \gamma = 0.5$), and paradigm 3 relied solely on the transient force profile ($\beta = 0, \gamma = 1$) (Fig. 2D).

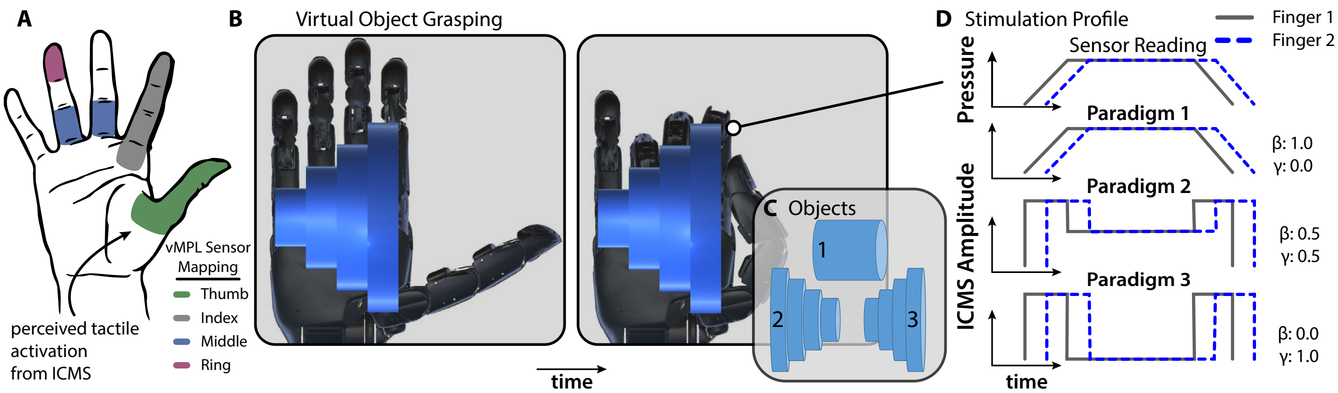

Fig. 2. (A) Map of perceived regions with artificial tactile sensations during ICMS. Electrodes were chosen to elicit sensory percepts in the shaded regions of the thumb, index, middle, and ring fingers. Electrodes corresponding to each region were stimulated based on the fingertip sensors in the virtual modular prosthetic limb. (B) Three different virtual objects were designed to create distinct spatiotemporal differences in the loading profile on the sensorized fingers of the virtual prosthesis. (C) The virtual Modular Prosthetic Limb (vMPL) was used to automatically grasp the objects. (D) ICMS to each region on the participant's hand was driven by the force profile from the respective fingertip sensor on the vMPL (only two fingertip force profiles shown for illustrative purposes). Three different stimulation paradigms were tested, each with different weighting of the sustained and transient components of the grip force.

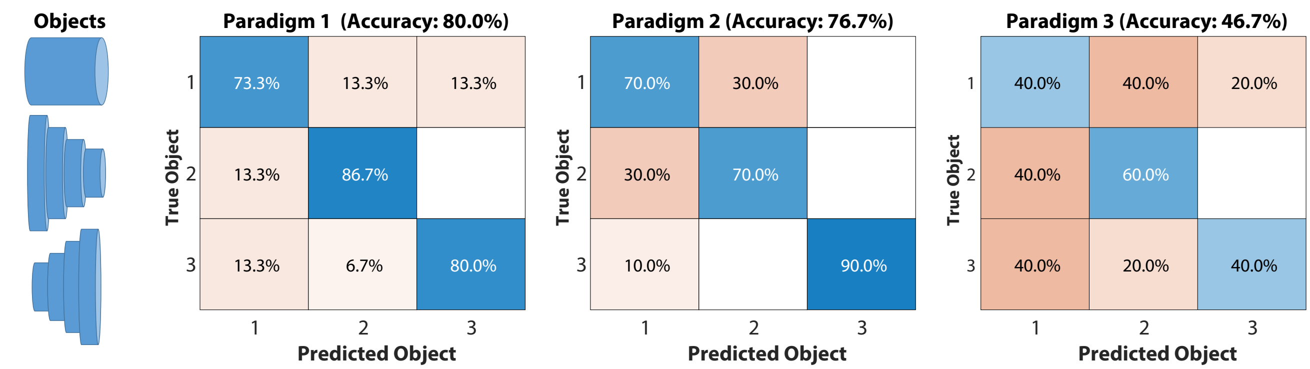

Fig. 3. Results from the object identification task. The participant used artifical tactile perceptions in his hand to predict which obect was being grasped by the virtual prosthetic hand. Performance was greater than 75% when using either stimulation paradigm 1 (sustained force component only, $\beta = 1.0, \gamma = 0$) or paradigm 2 (both sustained and transient force components, $\beta = 0.5, \gamma = 0.5$). Performance degraded, but was still above chance, when using stimulation paradigm 3 (transient force component only, $\beta = 0, \gamma = 1.0$).

The experiment was run on two sessions over a period of two weeks. Each of the stimulation paradigms was used for the object identification task and only one stimulation paradigm was used in each testing block. Each object was presented 15 times with stimulation paradigm 1, 10 times with paradigm 2, and 5 times with paradigm 3.

III. Results & Discussion

The global accuracy from the object identification task when using the sustained force profile to drive stimulation (paradigm 1) was 80% and 46.7% when using only the transient force component to drive ICMS amplitude (paradigm 3) (Fig. 3). When equally weighting both sustained and transient force to generate ICMS amplitude levels (paradigm 2), performance was 76.7%.

During the task, the participant described his strategy for identifying the different objects by focusing on the intensity of stimulation as well as the relative timing of sensation onset between the finger regions. The participant generally reported the predicted object shortly after contact was made in the virtual environment and did not seem to use any information from sensation *offset*. That is, he did not use, according to the participant, the relative timing as fingers released from the object because he felt as if the most useful information came at the onset of object contact. This combined use of spatial and temporal information from induced tactile sensations through direct cortical stimulation demonstrates the ability for users to intuitively integrate and utilize important features of touch sensation, similar to the natural behavior of mechanoreceptors in the periphery [9] and somatosensory neurons in the brain [10] during sensory stimulation of the skin, for accomplishing a tactile-related sensory task.

Regardless of the stimulation paradigm used, the participant was able to identify the objects with performance greater than chance. However, performance was markedly lower when using only the transient component of the grip force to drive stimulation amplitude (paradigm 3). In addition to fewer trials, the lower performance is likely because the duration of ICMS during paradigm 3 was shorter than in the other paradigms, resulting in much shorter tactile sensations only at the onset and offset of object contact. As a result, the participant seemed to have more difficulty picking up on the different spatiotemporal cues of the sensory activation in his hand. We believe this limitation can be addressed in future work by introducing and optimizing a smoothing filter on the the F_t signal component that drives ICMS amplitude.

An important observation is that using a cortical stimulation strategy that weighs both sustained and transient components of the grip force signal is a viable option for neuroprosthesis and BMI sensory feedback techniques. Restoring tactile sensations in a BMI can improve closed-loop control and functionality by using simple linear mapping of prosthesis grip force with ICMS amplitude [7]. The object identification results here demonstrate the feasibility for utilizing more biomimetic stimulation strategies to incorporate more complex components of touch, such as transient information, through direct brain stimulation during a neuroprosthesis or BMI task. Given the success of bioinspired stimulation modeling for peripheral nerve stimulation, it is reasonable to predict that similar strategies, by modeling somatosensory activity, would be beneficial in applications with direct brain stimulation for sensory feedback.

Critical to the safe and effective use of direct brain stimulation for sensory feedback is designing optimal stimulation paradigms to provide relevant sensory information while minimizing unnecessary or irrelevant information. It is still unclear how to best convey the most pertinent aspects of a sensory task through ICMS while minimizing injected current into the brain. In addition to the participant being able to identify the different objects through the various stimulation paradigms, we were able to reduce the overall ICMS amplitude during a given trial through the combined weighting of the sustained and transient components of the grip force (Fig. 2D). This is important because it demonstrates the feasibility of being able to provide relevant task information, through sensory feedback, while also reducing the injected charge into the brain. This will spur future work as we begin exploring the limits of reducing overall injected charge during stimulation while still preserving the ability to complete the task. Further, reduced power consumption, through reduced stimulation requirements, will benefit design and implementation of fully-implantable wireless systems for at-home use.

IV. CONCLUSIONS

We demonstrated that tactile sensations generated by ICMS of the somatosensory cortex can be used to identify different objects based on spatiotemporal features in the sensory feedback. Patterning ICMS based on biomimetic behavior, such as the natural response of cortical neurons to sustained and transient components of force on the skin, could be one way to improve how we convey artificial sensory information to the nervous system. We showed that using either the sustained component of a force signal or a weighted combination of both the sustained and transient force during an object grasping task with a virtual prosthetic hand can be used to effectively identify different shaped objects. Our results might suggest that only using the transient component of the force signal to drive stimulation amplitude is inadequate; however, our results are limited to a single participant and a simple identification task while also failing to fully explore the parameter space for fine tuning such a stimulation paradigm. Further work is needed to fully evaluate the potential differences and benefits of our proposed method. We believe using biomimetic strategies for direct brain stimulation will be a useful technique for providing more intuitive and feature-rich sensory feedback to neuroprosthesis and BMI users while also reducing the amount of overall injected current required to elicit necessary perceptions.

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