Mini-Symposia Title:

Recent Advances in Somatosensory Neuroprostheses - Part I

Mini-Symposia Organizer Name & Affiliation:

Emily Graczyk, PhD - Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH

Mini-Symposia Speaker Name & Affiliation 1:

Sliman J. Bensmaia, PhD - Department of Organismal Biology and Anatomy, University of Chicago, Chicago, IL

Mini-Symposia Speaker Name & Affiliation 2:

Hamid Charkhkar, PhD - Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH

Mini-Symposia Speaker Name & Affiliation 3:

Lee Fisher, PhD- Departments of Physical Medicine and Rehabilitation and Bioengineering , University of Pittsburgh,

Mini-Symposia Speaker Name & Affiliation 4:

Sathyakumar S Kuntaegowdanahalli, PhD - Dept. of Biomedical Engineering, Florida International University, Miami, FL

S Mini-Symposia Speaker Name & Affiliation 5:

Mini-Symposia Speaker Name & Affiliation 6:

Theme:

○ 01. Biomedical Signal Processing

○ 02. Biomedical Imaging and Image Processing

○ 03. Micro/ Nano-bioengineering; Cellular/ Tissue Engineering &

○ 04. Computational Systems & Synthetic Biology; Multiscale modeling

○ 05. Cardiovascular and Respiratory Systems Engineering

● 06. Neural and Rehabilitation Engineering

○ 07. Biomedical Sensors and Wearable Systems

○ 08. Biorobotics and Biomechanics

○ 09. Therapeutic & Diagnostic Systems and Technologies

○ 10. Biomedical & Health Informatics

○ 11. Biomedical Engineering Education and Society

○ 12. Translational Engineering for Healthcare Innovation and Commercialization

Mini-Symposia Synopsis— Max 2000 Characters

Limb loss and spinal cord injury result in physical and sensory deficits that limit independence and quality of life. For individuals with limb loss, advances in mechatronics have produced commercially-available dexterous prosthetic hands, multi-axis powered prosthetic ankles, and active knees. However, even the most advanced prostheses are still insensate tools, which severely limits their functionality compared to the dexterity and sophistication of intact biological limbs. In recent years, significant investment by agencies such as the Defense Advanced Research Projects Agency and the Department of Veterans Affairs have inspired researchers and engineers to develop novel approaches to restore sensation in people with sensorimotor impairment. In fact, this research has led to the development of bidirectional neuroprosthetic systems, which are already utilized by human subjects outside the laboratory at home and in the community. In the past several years, we have gained new knowledge on the physiological, psychophysical, and functional effects of elicited somatosensation in amputees and others with sensory deficits. In this mini-symposia, leading researchers in the field will present recent advances in sensory neuroprostheses, share some of the challenges in current approaches, and discuss future directions. Speakers will also discuss the implications of restored sensation on functional and psychosocial rehabilitation. We have assembled a diverse group of experts who have significantly contributed to sensory neuroprosthetic research and specialize in various approaches to restoring somatosensation, including peripheral nerve stimulation, intracortical stimulation, and spinal cord stimulation. Part 1 of this mini-symposia will provide an overview of the complexity of neural encoding of tactile information, recent work in touch models, several approaches to restoring sensory feedback to persons with limb loss, and home use studies of

Biomimetic Feedback Using a Whole Nerve Simulation

Sliman J. Bensmaia, PhD
Department of Organismal Biology and Anatomy, University of Chicago, Chicago, IL

Abstract— **Tactile signals from the hand are critical to our ability to grasp and manipulate objects. To achieve a dexterous bionic hand thus requires not only the restoration of volitionally controlled hand movements but also of tactile sensation. Tactile information is encoded in spatio-temporal patterns of activity across 12,000 nerve fibers of three different types, each with different response properties. A recently developed simulation can be used to simulate the response of these fibers to arbitrary patterns of skin deformation to inspire the development of sensory encoding algorithms for bionic hands.**

I. INTRODUCTION

Our ability to manipulate objects depends critically on the sense of touch as evidenced by the deficits produced when touch is abolished. The sense of touch is primarily mediated by 12,000 or so nerve fibers that innervate the palmar surface of the hand. These populations can be broken down into three types – slowly adapting type 1 (SA1), rapidly adapting (RA), and Pacinian-corpuscle associated (PC) – each of which responds to different aspects of skin deformation. Natural interactions with objects give rise to the activation of hundreds or thousands of nerve fibers, each responding in an idiosyncratic way that depends on its type (SA1, RA, or PC) and on the location of its receptive field on the skin.

Given the importance of touch most manual behaviors, to achieve a dexterous bionic hand will require that tactile signals be restored. The ideal sensory feedback would mimic the signals produced in the intact hand. A perfect biomimetic algorithm would require (1) characterizing how each afferent responds to a pattern of stimulation of bionic hand (sensed artificially through an artificial skin) and (2) activating each nerve fiber with an appropriate pulse train, which would require 12,000 independent stimulation channels.

While current stimulation strategies do not provide the bandwidth to restore natural touch, a recently developed stimulation can be invoked to develop sensory feedback algorithms that lead to maximally biomimetic patterns of neural activation given the limitations of the existing technology.

II. METHODS

We have developed a model – dubbed TouchSim – that simulates the responses of all tactile fibers innervating the glabrous skin of the hand to any spatiotemporal stimulus applied to the skin [1]. The model first reconstructs the stresses experienced by mechanoreceptors when the skin is deformed and then simulates the spiking response that would be produced in the nerve fiber innervating that receptor. By simulating skin deformations across the palmar surface of the hand and tiling it with receptors at their known densities, we reconstruct the responses of entire populations of nerve fibers.

III. RESULTS

We show that the simulated responses closely match their measured counterparts, down to the precise timing of the evoked spikes, across a wide variety of experimental conditions sampled from the literature. We then discuss how the model provides a means to establish naturalistic artificial touch in bionic hands and show some recent results demonstrating improved manual dexterity with biomimetic feedback compared to the traditional feedback that simply tracks sensory output by modulating stimulation frequency or amplitude [2,3].

IV. DISCUSSION & CONCLUSION

TouchSim can be used to develop sensory feedback algorithms that are tailored to the technology used to activate the nerve, regardless of the number of channels. As the number of stimulation channels increases and their ability to selectivity activate individual nerve fibers improves, the resulting tactile feedback will be increasingly verisimilar.

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Sliman Bensmaia is in the Department of Organismal Biology and Anatomy at the University of Chicago, Chicago, IL 60637 USA, phone: 773.834.5203; e-mail: sliman@uchicago.edu).

Functional Effects of Sensory Neuroprosthesis in Individuals with Lower Limb Amputation

Hamid Charkhkar, PhD
Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH
Louis Stokes Cleveland Veteran Affairs Medical Center, Cleveland, OH

I. INTRODUCTION

Although state-of-the-art prosthetic technologies for lower limb amputees, such as microprocessor knees and powered ankles, have provided users with some improvement in function, such prostheses still cannot provide natural somatosensory feedback related to the lost limb. Plantar foot sensation and proprioception from lower limb joints play important roles in maintaining balance and stabilizing gait [1]. Specifically, individuals with lower limb amputation face challenges in maintaining their balance especially when navigating uneven terrains or encountering perturbations during walking in part due to compromised sensation. In addition, compared to able-bodied individuals, lower limb amputees exhibit increased risk for trips and falls, lower mobility in the dark, poor gait dynamics and heightened fear of falling. Electrical stimulation of the remaining nerves in the residual limb of lower limb amputees via various neural interface technologies can elicit somatosensory percepts referred to the missing limb [2]. As such, prosthetic devices could be developed to provide useful feedback from foot-floor interactions. In my talk, I will cover effects of a sensory neuroprosthesis on objective measures of balance and gait. In addition, I will show some preliminary results on the use of the sensory neuroprosthesis at home and in community.

II. METHODS

Electrical stimulation was delivered via nerve cuff electrodes implanted in the residual limb of transtibial amputees on pre-branch sciatic and post-branch tibial nerves. Stimulation elicited tactile sensation or proprioception.

We developed an instrumented prosthesis equipped with pressure sensors embedded in shoe insoles. When pressure sensors were activated, appropriate electrical stimulation was delivered to the nerve via cuff electrodes to evoke sensation either at areas of the missing toes, heel, or the plantar surface of the foot. Stimulation parameters were varied proportionally in response to pressure readings from the pressure sensors to modulate the intensity of the perceived sensation.

We examined the effect of sensory feedback on static balance using a clinically known test, sensory organization test during which body's sensory systems (visual, vestibular, and somatosensory) are perturbed in a controlled fashion.

For the home-going trial, a series of in-person assessments was performed prior, during, and at the end of the trial to determine subjective reports of safety, balance confidence, incidence of falls and pain. Furthermore, during this trial, we characterized subject performance in functional activities such as negotiating uneven terrain, stair ascent/descent with and without a clear view of steps, and walking with and without distraction.

III. RESULTS & DISCUSSION

Our findings suggest that restoring sensory feedback to individuals with lower- limb loss could potentially minimize overuse of their intact limbs and improve postural stability in response to perturbations. Our observations also suggest that lower-limb amputees could improve their standing stability using sensory feedback elicited by neural stimulation, though the extent of such improvement depends on reliability and availability of other sensory inputs. Evidence from prior work indicate direct correlation between static balance and walking ability in lower-limb amputees corroborated with preliminary findings in this study. Furthermore, our results indicate that electrically induced sensory feedback is integrated into the nervous system similar to the natural sensation. In conclusion, our observations suggest incorporation of sensory feedback from the missing limb in currently available lower limb prostheses could further improve the functionality of such devices.

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Hamid Charkhkar is with the Department of Biomedical Engineering, Case Western Reserve University and Louis Stoke Cleveland Veteran Affairs Medical Center, Cleveland, OH 44106 USA. (e-mail: hamdi.charkhkar@case.edu).

Spinal Cord Stimulation to Restore Sensation After Limb Amputation

Lee Fisher, PhD
Departments of Physical Medicine and Rehabilitation and Bioengineering , University of Pittsburgh, Pittsburgh, PA

I. INTRODUCTION

Despite major advances in prosthetics, adoption rates remain poor, in part because they provide limited somatosensory feedback. Recent studies have shown that restored feedback can improve control of prostheses, although widespread clinical dissemination of these technologies has yet to occur. Here, we report on results from a study to restore somatosensory feedback in individuals with upper- and lower-limb amputation by stimulating the spinal cord at the cervical and lumbosacral levels, respectively. The spinal cord stimulation (SCS) electrodes used in this study are commonly used clinically to treat intractable low back and limb pain, and are implanted in as many as 50,000 people per year with a low rate of complications. This high degree of clinical utilization provides a clear path for rapid clinical translation of these sensory restoration techniques. In this talk, I will describe the results of these ongoing studies in terms of the location, quality, and intensity of sensory percepts evoked by stimulation, the effects of those sensory percepts on closed-loop control of prosthetic limbs, and the reductions in phantom limb pain (PLP) that we have observed during use of the somatosensory neuroprosthesis.

II. METHODS

To date, spinal cord stimulation has been used to evoke sensations in the missing hand and arm of four subjects with upper-limb amputation and in the foot and leg of one subject with lower-limb amputation. All experiments were performed under the approval of the University of Pittsburgh Institutional Review Board. In all subjects, three 8- or 16-contact SCS leads were percutaneously implanted into the epidural space near the spinal cord for ≤29 days and connected to an external stimulator.

Subjective and psychophysical measures were used to quantify the subjects' perception of sensation. After 1s long stimulus trains, subjects were instructed to draw the location of the evoked sensation and to describe various qualities of the sensation, including intensity and modality. Detection thresholds and just-noticeable differences (JND) were measured using a two-alternative forced choice task. In these tasks, stimulation was delivered during two intervals, and amplitude was varied with respect to a reference amplitude. The subjects were instructed to state which interval contained the stimulus for the detection task, or which interval contained the stronger stimulus for the JND task.

In two upper-limb amputees, closed-loop tasks were performed in which the subject controlled a virtual or physical robotic hand to grasp objects of different size and stiffness while sensory feedback was modulated in proportion to signals recorded from sensors in the fingertips. Subjects were instructed to state the size and/or stiffness of the objects while blindfolded as a measure of their ability to incorporate the sensory feedback into their control of the prosthetic limb.

For all subjects, phantom limb pain was quantified using the McGill Pain Questionnaire (MPQ), which was administered once before implantation, weekly during the 29-day study, and one month after explantation of the leads.

III. RESULTS

In four upper-limb amputees, stimulation at the cervical spinal cord evoked sensations in the missing fingers, hand, and arm. Sensations were stable during the 29-day implant, with intensity modulated by stimulus amplitude and frequency. During closed-loop tasks, two subjects were able identify object size and/or stiffness as levels exceeding chance when sensory feedback was delivered by cervical SCS. In one lower-limb amputee, lumbosacral SCS evoked sensations localized to the foot and ankle. In that subject, only stimulation frequencies above 200 Hz evoked sensations in the missing limb, while lower frequencies produced sensations in the residual limb. In all subjects that presented with PLP (i.e. 4 of 5), there was a clinically meaningful (i.e. >5 point) decrease in MPQ scores during the study, with three subjects experience decreases of 20 points or more.

IV. DISCUSSION & CONCLUSION

These results suggest that SCS is a viable option for providing sensory feedback from prosthetic limbs after both upper- and lower-limb amputation, and that sensory feedback can have important effects on PLP. Future work will focus on longer duration implants, more details characterization of the perception of sensations evoked by PLP, and more complex demonstrations of closed-loop use of the systems, including tasks involving balance control and gait stability in people with lower-limb amputation.

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L.E. Fisher is in the Departments of Physical Medicine and Rehabilitation and Bioengineering at the University of Pittsburgh, Pittsburgh, PA 15213; e-mail: lef44@pitt.edu).

A Neural Enabled Prosthetic Hand System for Sensory Restoration

Sathyakumar S Kuntaegowdanahalli, PhD
Dept. of Biomedical Engineering, Florida International University, Miami, FL

Abstract— **Today's prosthetic hand systems do not fully meet the needs of individuals with upper limb amputation, in part because they do not provide sensory feedback regarding the actions of the prosthetic hand. This limits functional capabilities, increases attentional demands, affects quality of life, and also disrupts body image. We have addressed this gap by developing the ANS-NEPH System for use in real-world environments.**

I. INTRODUCTION

Upper limb loss can have a profound impact on a person's capacity to perform activities of daily living and likely result in a reduced level of autonomy for the person. Although significant advances have been made in prosthetic technologies for individuals with upper limb amputation, current day prostheses are still limited in their ability to fully restore function after limb-loss. Today's state-of-the-art prosthesis-a myoelectrically controlled motorized device, while being a significant improvement over the cable operated prosthetic hand in many aspects, is still difficult to control due to limited sensory feedback.

II. METHODS

To address this problem, the Adaptive Neural System's lab has developed the Neural Enabled Prosthetic Hand (NEPH) system to provide individuals with upper limb amputation with sensations that follow the sensor-derived signals from a myoelectrically controlled prosthetic hand. The system includes an implanted neurostimulator to deliver electrical pulses via fine-wire longitudinal intrafascicular electrodes implanted in peripheral nerves of the residual limb. The neurostimulator is driven by an external, prosthesis socket-mounted interface module that utilizes a wireless link to communicate stimulation commands to the implant unit. The NEPH system is designed to be self-contained, reliable, and easy to maintain and use on a daily basis. An investigational device exemption has been secured from the FDA and a first-in-human early feasibility clinical trial to evaluate the NEPH system in individuals with upper limb amputation is underway.

III. RESULTS

The NEPH system has been deployed in one person with transradial amputation for over 20 months with the subject using the device outside the lab for over 16 months. Indications from tests for system functionality are encouraging. Also, there have been no serious adverse events or safety concerns.

IV. DISCUSSION & CONCLUSION

Early indications are that the NEPH system with an intrafascicular neural interface can provide functionally meaningful sensations that can be utilized by individuals with an upper extremity amputation to better control their prosthesis. The suitability of the NEPH system for daily use in real-world environments makes it a good platform technology to investigate the long-term effects of restoring sensation on functional capabilities, body image, and quality of life.

ACKNOWLEDGMENT

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Sathyakumar S. K. is with Dept. of Biomedical Engineering, 10555 W Flagler St, Florida International University, Miami, FL, USA 33174, USA, phone: 305-348-4780; e-mail: skuntaeg@fiu.edu).