Mini-Symposia Title:

Recent Advances in Somatosensory Neuroprostheses - Part II

Mini-Symposia Organizer Name & Affiliation:

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

Mini-Symposia Speaker Name & Affiliation 1:

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

Mini-Symposia Speaker Name & Affiliation 2:

Jacob L. Segil, PhD- Rocky Mountain Regional VA Medical Center, Aurora, CO

Mini-Symposia Speaker Name & Affiliation 3:

Breanne P. Christie, PhD - Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH

Mini-Symposia Speaker Name & Affiliation 4:

Chris Hughes, MS - Rehab Neural Engineering Labs, University of Pittsburgh, Pittsburgh, PA

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

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-symposium, 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 2 of this mini-symposia will explore artificial intelligence approaches for understanding perception and advancing neurostimulation, sensorimotor integration of neurostimulation in functional tasks, and recent work in intracortical

Artificial Intelligence to Enhance Sensory Neurostimulation

Emily L. Graczyk, PhD
Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH
Louis Stokes Cleveland Veteran Affairs Medical Center, Cleveland, OH

***Abstract*—Artificial intelligence (AI) is an important tool for decoding neural activity in brain-computer interfaces. While AI is most commonly used to classify motor intent from cortical or muscle recordings, it can also be used to understand sensory neural activity and sensory perception. I will present several recent works integrating AI approaches into sensory neuroprostheses.**

I. Introduction

Sensory neurostimulation involves applying electrical pulses to the somatosensory nervous system through implanted neural interfaces. This technique can be used to provide sensory feedback to persons with sensory deficits due to amputation, spinal cord injury, or other neurological conditions. Stimulation of upper extremity nerves can evoke tactile and proprioceptive percepts on the hand and fingers that can be scaled in perceived magnitude [1].

Evoking natural sensation qualities is a critical goal for sensory neurostimulation systems. However, there are two key difficulties in improving the quality of sensations from stimulation. First, quality is subjective and difficult to analyze across participants. To combat this issue, multi-dimensional scaling has been used previously to understand the dimensionality of tactile qualities in natural touch and to make comparisons across groups of able-bodied participants [2]. Second, the neural determinants of natural quality are not fully understood. Because of this, it is difficult to design advanced stimulation paradigms to better convey qualitative information or to increase the bandwidth of sensory information provided to the user. In this talk, I will demonstrate how AI approaches can be used to address these difficulties and thereby enhance sensory neuroprostheses.

II. Methods

We applied dimensionality reduction techniques to perceived quality data from seven upper and lower limb amputee participants receiving peripheral nerve stimulation from implanted cuff electrodes. The participants rated 30 qualitative descriptors for electrical stimuli that varied in pulse width and pulse frequency. We ran individual and group multi-dimensional scaling analyses to understand the dimensionality of the artificial quality space and correlation analyses to compare each MDS dimension to the two stimulation parameters.

In another computational project, we used artificial intelligence to extract the key neural features of touch based on biophysical models of normal touch [3]. We then utilized neural networks and an electrical model to build a controller for peripheral nerve stimulation to evoke the extracted neural features.

*Research supported by the Defense Advanced Research Projects Agency (DARPA) Biological Technologies Office (BTO) under the HAPTIX program (Pacific Contract No. N66001-15- C-4014) and the INI program (Contract number: HR00111990044).

Emily Graczyk is with the Department of Biomedical Engineering at Case Western Reserve University, Cleveland, OH 44106 USA, phone: 216-791-3800 x63571; e-mail: emily.graczyk@case.edu.

III. Results & Discussion

We found that sensory percepts evoked by peripheral nerve stimulation were typically best described in three dimensions and that the primary dimension significantly correlated with stimulation pulse frequency. However, both stimulation pulse width and pulse frequency modulated the sensory quality.

From the computational analysis of neural features, we found that touch-related neural activity is highly compressible and that shared feature spaces could represent multiple touch stimuli simultaneously with low error. These AI approaches could be applied to examine the neural correlates of perception without requiring extensive animal or human testing. The stimulation controller modulated pulse parameters on a pulse-by-pulse basis for groups of contacts in a peripheral cuff electrode to recruit appropriate neural population activity over time. In the future, we will test the stimulation controller in human participants to increase the information bandwidth of peripheral nerve stimulation.

IV. Conclusion

AI enables a better understanding of the perception and neural coding of touch sensation. AI approaches should be integrated into sensory neuroprostheses to provide more natural, useful percepts to people with sensory deficits.

References

[1] E. L. Graczyk, M. A. Schiefer, H. P. Saal, B. P. Delhaye, S. J. Bensmaia, and D. J. Tyler, “The neural basis of perceived intensity in natural and artificial touch,” *Sci. Transl. Med.*, vol. 8, no. 362ra142, pp. 1–11, 2016.

[2] M. Hollins, S. Bensmaïa, K. Karlof, and F. Young, “Individual differences in perceptual space for tactile textures: evidence from multidimensional scaling.,” *Percept. Psychophys.*, vol. 62, no. 8, pp. 1534–44, Nov. 2000.

[3] H. P. Saal, B. P. Delhaye, B. C. Rayhaun, and S. J. Bensmaia, “Simulating tactile signals from the whole hand with millisecond precision,” *Proc. Natl. Acad. Sci.*, vol. 114, no. 28, pp. E5693–E5702, 2017.

Towards the Embodiment of Prosthetic Hands: Advances in Biomechatronic Design and Control

Jacob L. Segil, PhD
Rocky Mountain Regional VA Medical Center, Aurora, CO
Department of Mechanical Engineering, University of Colorado at Boulder, Boulder, CO

***Abstract*— The embodiment of artificial devices by providing physiologically appropriate somatosensory feedback is now possible leveraging advancements in neural interfaces, biomechatronic devices, and myoelectric control algorithms. Neural interfaces like the Flat Interface Nerve Electrode (FINE) developed at Case Western Reserve University can elicit sensory percepts across a range of spatial locations in a simultaneous manner allowing full hand sensory percepts for upper limb amputees. Previous work by the authors have shown the ability to integrate five simultaneous percepts in order to identify grasping patterns of a hidden prosthetic hand. In parallel, the development of advanced fingertip sensors enables the use of both touch (force measurements) with proximity (distance measurements) in order to provide multi-modal information to the user and artificial device. Experimental work will be presented which shows the utility of the force feedback to the user as well as the use of the proximity feedback to augment the efficacy of the myoelectric control schemes. Finally, future questions regarding the preferred myoelectric control method to elicit embodiment and the utility of full-hand sensation on embodiment will be discussed.**

* Research supported by Career Development Award IK1RX00201 from the United States Department of Veterans Affairs Rehabilitation R&D Service.

Electrically-evoked somatosensation in lower-limb amputees improves performance on an ambulatory searching task

Breanne P. Christie, PhD
Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH
Louis Stokes Cleveland Veteran Affairs Medical Center, Cleveland, OH

I. INTRODUCTION

Despite technological advances in prostheses, below-knee amputees (BKAs) still face locomotor challenges. BKAs have a higher fall risk and compensatory gait patterns [1], which leads to long-term musculoskeletal damage [2]. One reason why current prostheses have limited effectiveness in addressing these deficits may be because locomotion is a sensorimotor task, and the sensory component is largely unaddressed by current technologies.

Sensory information can be incorporated into a prosthesis by electrically stimulating the residual nerves of amputees to elicit somatosensory percepts referred to the missing limb. However, the functional benefits of sensory-enabled lower-limb prostheses are not well understood. In this study, our first goal was to quantify how able-bodied individuals and BKAs performed on an ambulatory searching task that stressed the role of cutaneous plantar sensation. Our second goal was to evaluate lower-limb amputees' performance on the test while using a somatosensory-enabled prosthesis.

II. METHODS

The horizontal ladder walking test has been used to evaluate cutaneous sensation in animal models [3]. In the present study, 14 able-bodied individuals and six BKAs performed an adapted version of this test while blindfolded. Two BKAs repeated the test using sensory neuroprostheses. These individuals had nerve cuff electrodes installed around their residual sciatic nerves. Closed-loop electrical stimulation was triggered and modulated by readings from pressure insoles placed underneath the prostheses. Stimulation parameters were selected to elicit sensations projected to a region of the missing foot that matched the activated insole region. We measured completion time, number of foot placement errors, and foot placement strategy (i.e., the region of the foot on the ladder rung). Errors included missing a rung, slipping off a rung, and placing the foot on two rungs at once.

III. RESULTS

BKAs and able-bodied individuals took similar amounts of time to cross the ladder. BKAs made significantly more foot placement errors than able-bodied individuals ($p=0.003$), with the majority of errors made by the prosthetic limb. For BKAs, there was a speed-accuracy tradeoff: trials with lower completion times had significantly more errors ($p<0.001$). The use of a sensory neuroprosthesis significantly improved this trade-off for both BKAs (Fig. 1). Trial completion time decreased for participant BKA01 ($p=0.01$) and error rate deceased for participant BKA02 ($p<0.001$).

Able-bodied individuals typically used the forefoot to step on a ladder rung, while BKAs preferred the midfoot for both limbs. The use of a sensory neuroprosthesis did not change foot placement strategy.

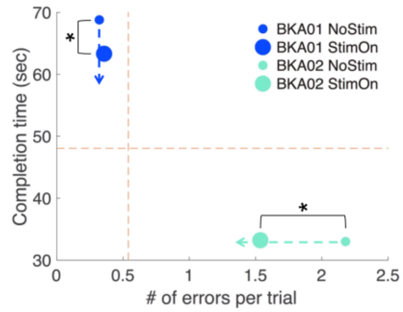

Figure 1. Improvements in the speed-accuracy trade-off when wearing sensory neuroprostheses ('StimOn') versus standard prostheses ('NoStim'). Mean able-bodied results are depicted with dashed orange lines.

IV. DISCUSSION & CONCLUSION

In addition to characterizing the efficacy of lower-limb sensory neuroprostheses, this study advanced our understanding of how cutaneous plantar sensation can be used to acquire action-related information during challenging locomotor tasks. Improvements in the speed-accuracy tradeoff demonstrated that there is an immediate benefit of sensory neuroprostheses for BKAs. Invariable foot placement strategies indicate that long-term rehabilitative benefits, such as improved body weight symmetry, may require a prescribed training regime. Overall, this study provides a foundation upon which to build future investigations into the role of somatosensation in bipedal ambulation in persons with or without limb loss.

REFERENCES

[1] J. Paysant et al., "Influence of terrain on metabolic and temporal gait characteristics of unilateral transtibial amputees." *Journal of Rehabilitation Research & Development* 43.2 (2006).

[2] R. Gailey et al., "Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use." *Journal of Rehabilitation Research & Development* 45.1 (2008).

[3] L.J.G. Bouyer, S. Rossignol, "Contribution of cutaneous inputs from the hindpaw to the control of locomotion. II. Spinal cats." *Journal of neurophysiology* 90.6 (2003): 3640-3653.

*Research supported by DARPA N66001-15-C-4038.

B.P.C. is with Case Western Reserve University and Louis Stokes Cleveland VA Medical Center, Cleveland, OH 44106 USA, phone: 216-791-3800 x62921; e-mail: bpc31@case.edu.

Recent advances in intracortical microstimulation for sensory restoration

Chris Hughes, MS
Rehab Neural Engineering Labs, University of Pittsburgh, Pittsburgh, PA

Abstract— **Somatosensation is crucial for motor control and is an important part of the human experience. In an ongoing experiment, we are studying the use of intracortical microstimulation (ICMS), delivered through Utah arrays implanted in somatosensory cortex, to restore tactile percepts in a human participant with a C5/C6 spinal cord injury. We have previously demonstrated that ICMS can elicit tactile percepts on the hand that are somatotopically organized. Our recent work has focused on studying how parameters of stimulation, such as pulse amplitude and frequency, can impact tactile perception. To understand how amplitude and frequency impact intensity and quality of tactile perception, we have used a combination of survey and magnitude estimation experiments. We have found that fixed increases in amplitude lead to linear increases in intensity but have no notable effects on perceptual quality. Fixed frequency changes, however, modulate intensity in a non-linear, electrode dependent manner and have strong effects on evoked quality. Motivated by these findings, we wanted to understand what aspect of frequency modulates perception: the overall stimulus rate or the time between individual pulses. To understand this, we performed a same-different task in which pulse trains with fixed interpulse timings were compared to pulse trains of the same overall frequency with variable interpulse timings. We found that variable interpulse timings could alter tactile perception on about half of the tested electrodes, with interpulse shifts of 15-20 ms producing differences that were perceptible 75% of the time. These findings indicate that the cortex is sensitive to multiple aspects of stimulation, including the amount of neurons recruited, the stimulus rate, and the timing of stimulus events. To optimally provide sensory feedback, we will need to develop algorithms that utilize these different response properties for natural and intuitive sensory encoding, such as in a biomimetic encoding algorithm.**

* This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA) and Space and Naval Warfare Systems Center Pacific (SSC Pacific) under Contract No. N66001-16-C-4051 and the Revolutionizing Prosthetics program (contract number N66001-10-C-4056). Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of DARPA or SSC Pacific. Additionally, this material is based on work supported by the National Institutes of Health (1UH3NS107714-01).

Chris Hughes is with the University of Pittsburgh, Pittsburgh, PA 15260 USA, phone: (412) 383-1077; email: clh180@pitt.edu.