FAU COLLEGE OF ENGINEERING AND COMPUTER SCIENCE
FLORIDA ATLANTIC UNIVERSITY

Announces the Ph.D. Dissertation Defense of

Craig Ades

for the degree of Doctor of Philosophy (Ph.D.)

"Embodied Biological Computers: Closing the Loop on Sensorimotor Integration of Dexterous Robotic Hands"

In Person Meeting:
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Engineering west (Building 36), Conference Room 187
777 Glades Road
Boca Raton, FL

Zoom Meeting
Meeting ID: 862 1874 3287
Passcode: Cnkg9E

DEPARTMENT:
Ocean and Mechanical Engineering

ADVISOR:
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Erik D. Engeberg, Ph.D., Chair
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ABSTRACT OF DISSERTATION
"Embodied Biological Computers: Closing the Loop on Sensorimotor Integration of Dexterous Robotic Hands"

The sensation of touch is an integral part of using our hands. As different researchers work toward the restoration of afferent sensation in prosthetic hands, it becomes urgent to better understand how an artificial hand's afferent inputs are affected by the efferent muscular outputs, and vice-versa. Current methods of neuroprosthetic research have many regulatory hurdles, time, cost, and associated risk to the patient. To circumvent these hurdles, we developed a non-invasive, closed-loop (CL) neuroprosthetic research platform, integrating artificial tactile signals from an artificial hand with biomimetically-stimulated biological neuronal networks (BNNs) cultured in a multielectrode array (MEA) chamber. These living embodied biological computers (EBCs) can provide a non-invasive alternative for investigating invasive neuroprosthetic interfaces. With them we can explore a variety of control techniques, tactile sensation encoding methods, and neural decoding methods to increase the rate of research in this area with minimal regulatory approval, greatly reduced cost and time, and no risk to the patients.

In the first stage of this integration, our EBC was programmed to embody neuronal spiking from spontaneously active "efferent" receptive fields in cultured BNNs as intentional signals for movement. Bursts were transferred to a robotic hand and initiated a tapping motion of the index finger laid in proximity to a surface. Contact elicited artificial sensations, which were registered by a biotac tactile sensor array fit to the robotic fingertip. Neurocomputational models converted tactile pressures into firing patterns tuned to mimic rapidly adapting (RA) and slowly adapting (SA) mechanoreceptors. Those firing patterns were returned to electro-stimulating electrodes of the MEA assigned afferent functions. Experimentation explored multiple permutations of peripheral-neural coupling: afferent deprivation (AD) (motor control with no sensation), efferent substitution (ES)

(sensation with fixed motor control), and CL coupling (sensorimotor interaction). We demonstrate that embodied behavior is affected by the RA and SA encoding methods through the statistically significant behavior of the artificial hand's tapping rate, measured as inter-tapping-interval (ITI). Comparison of the spontaneous motor pool activation recorded during afferent deprivation permutations to the neural activity during CL coupling revealed functionalization of afferent and efferent communication in the neural culture, that is, a primitive form of sensorimotor computation. Offline analysis using transfer learning further revealed the functional specialization through the statistically significant classification accuracies. Those results suggest that neuronal cultures can learn complex sensorimotor associations with robotic systems.

By harnessing this functional specialization, we furthered our study and deployed this closed-loop paradigm to investigate the reflex and perceptive abilities of a human-in-the-loop (HIL), coupled to a dexterous robotic hand through the EBC. We investigated this from two relative perspectives: (1) the ability for an artificial hand's tactile interaction to evoke a response from the EBC due to a variety of robot-to-synapse (robosynape) encoding methods representing mechanoreceptor firing patterns naturally present in an intact hand, and (2) the ability for those evoked neural responses to be relayed to the HIL through vibrotactile feedback (neurohaptics). We evaluated the electromyography (EMG) response of one upper limb-absent subject and five able-bodied subjects to the tactile interactions of the artificial hand with the EBC relative to the different robosynaptic encoding methods. Comparisons of baseline neuronal EBC activity to embodied activity showed statistical significance in spatiotemporal correlation, indicating sensorimotor integration with the neurorobotic platform. Further comparisons of the robosynaptic encoding methods to the HIL EMG responses showed the RA and Biomimetic encoding methods similar in function to that of the control stimulation for discrete events and dissimilar to the SA and linear PFM encoding methods. This demonstrated functional specialization of the robosynaptic encodings, providing meaningful information to the HIL for the discrete event paradigm of detecting onsets and offsets of contact. This type of work opens research for invasive models to be explored in a non-invasive paradigm for expanding the scientific community and enhancing our overall knowledgebase as a species.

Ultimately, what we investigated here are the fundamental components of the sensorimotor system, where biological matter has formed structures in such a way to produce varying levels of behavioral function. This novel neuroprosthetic research platform has made a significant contribution in furthering the understanding of natural sensorimotor interaction. This approach provides a non-invasive model for investigating sensorimotor interactions between the encoding and decoding of state-of-the-art invasive neuroprosthetic solutions with a HIL. This type of a platform poses a medium for asking and answering many of these questions and making this more a possibility than ever before. This model can be duplicated, and multiple EBCs connected in parallel to increase the throughput rate and explore multidimensional interactions. A long-term opportunity of this work is the creation of biological computers to assist neuroprosthetic hands with fully integrated artificial reflexes, that is, a form of edge computing for neurotechnological interfaces.

BIOGRAPHICAL SKETCH
Born in Plantation, Florida
B.S., Florida Atlantic University, Boca Raton, Florida, USA, 2015
M.S., Florida Atlantic University, Boca Raton, Florida, USA, 2018
Ph.D., Florida Atlantic University, Boca Raton, Florida, USA, 2022

CONCERNING PERIOD OF PREPARATION
& QUALIFYING EXAMINATION

Time in Preparation: 2015-2022

Qualifying Examination Passed: 2017

Published Papers:

Journal Publications

1. **C. J. Ades et al., "Shape memory alloy tube actuators inherently enable internal fluidic cooling for a robotic finger under force control," Smart Materials and Structures, vol. 29, no. 11, p. 115009, 2020.**
2. **M. A. Abd, I. Gonzalez, C. Ades, M. Nojoumian, and E. D. Engeberg, "Simulated robotic device malfunctions resembling malicious cyberattacks impact human perception of trust, satisfaction, and frustration," International Journal of Advanced Robotic Systems, vol. 16, no. 5, p. 1729881419874962, 2019.**

Conference Papers

1. **C. Ades et al., "Robotic Finger Force Sensor Fabrication and Evaluation Through a Glove," in Proceedings. Florida Conference on Recent Advances in Robotics, 2018, vol. 2018, pp. 60-65. Soft Robotic Actuator Design and Control**
2. **J. Ingicco, M. AlSaidi, M. Abd, C. Ades, and E. Engeberg, "Force and Pressure Control of Soft Robotic Actuators," in Proceedings. Florida Conference on Recent Advances in Robotics, 2018, vol. 2018: NIH Public Access, p. 39.**
3. **M. A. Abd, C. Ades, et al., "Impacts of soft robotic actuator geometry on end effector force and displacement," in 30th Florida Conference on Recent Advances in Robotics, May, 2017, pp. 11-12.**
4. **C. Ades et al., "Robotically Embodied Biological Neural Networks to Investigate Haptic Restoration with Neuroprosthetic Hands," in 2022 IEEE Haptics Symposium (HAPTICS), 2022: IEEE, pp. 1-7.**