

Novel Framework of Online, Task-Independent Cognitive State Transition Detection and Its Applications

By
Xiaoxu Kang

A dissertation submitted to The Johns Hopkins University in conformity with the
requirements for the degree of Doctor of Philosophy.

Baltimore, Maryland

August, 2014

©Xiaoxu Kang 2014

All rights reserved

Abstract

Complex reach, grasp, and object manipulation tasks require sequential, temporal coordination of a movement plan by neurons in the brain. Detecting cognitive state transitions associated with motor tasks from sequential neural data is pivotal in rehabilitation engineering.

The cognitive state detectors proposed thus far rely on task-dependent (TD) models, i.e., the detection strategy exploits *a priori* knowledge of the movement goals to determine the actual states, regardless of whether these cognitive states actually depend on the movement tasks or not. This approach, however, is not viable when the tasks are not known *a priori* (e.g., the subject performs many different tasks) or when there is a paucity of neural data for each task. Moreover, some cognitive states (e.g., holding) are invariant to the tasks performs.

I first develop an offline, task-dependent cognitive state transition detector and a kinematics decoder to show the feasibility of distinguishing between cognitive states based on their inherent features extracted via a hidden Markov model (HMM) based detection framework. The proposed framework is designed to decode both cognitive states and kinematics from ensemble neural activity. The proposed decoding framework is able to a) automatically differentiate between baseline, plan, and movement, and b) determine novel holding epochs of neural activity and also estimate the epoch-dependent kinematics. Specifically, the framework is mainly composed of a hidden Markov model (HMM) state decoder and a switching linear system (S-LDS) kinematics decoder. I take a supervised approach and use a generative framework of neural activity and kinematics. I demonstrate the decoding framework using neural recordings from ventral premotor (PMv) and dorsal premotor (PMd) neurons of a non-human primate executing four complex reach-to-grasp tasks along with the corresponding kinematics recording. Using the HMM state decoder, I demonstrate that the transitions between neighboring epochs of neural activity, regardless of the

existence of any external kinematics changes, can be detected with high accuracy (>85%) and short latencies (<150 ms). I further show that the joint angle kinematics can be estimated reliably with high accuracy (mean = 88%) using a S-LDS kinematics decoder. In addition, I demonstrate that the use of multiple latent state variables to model the within-epoch neural activity variability can improve the decoder performance. This unified decoding framework combining a HMM state decoder and a S-LDS may be useful in neural decoding of cognitive states and complex movements of prosthetic limbs in practical brain-computer interface implementations.

I then develop a real-time (online) task-independent (TI) framework to detect cognitive state transitions from spike trains and kinematic measurements. I applied this framework to 226 single-unit recordings collected via multi-electrode arrays in the premotor dorsal and ventral (PMd and PMv) regions of the cortex of two non-human primates performing 3D multi-object reach-to-grasp tasks, and I used the detection latency and accuracy of state transitions to measure the performance. I found that, in both online and offline detection modes, (i) TI models have significantly better performance than TD models when using neuronal data alone, however (ii) during movements, the addition of the kinematics history to the TI models further improves detection performance. These findings suggest that TI models may be able to more accurately detect cognitive state transitions than TD under certain circumstances. The proposed framework could pave the way for a TI control of prosthesis from cortical neurons, a beneficial outcome when the choice of tasks is vast, but despite that the basic movement cognitive states need to be decoded.

Based on the online cognitive state transition detector, I further construct an online task-independent kinematics decoder. I constructed our framework using single-unit recordings from 452 neurons and synchronized kinematics recordings from two non-human primates performing 3D multi-object reach-to-grasp tasks. I find that (i) the proposed TI framework performs

significantly better than current frameworks that rely on TD models ($p = 0.03$); and (ii) modeling cognitive state information further improves decoding performance. These findings suggest that TI models with cognitive-state-dependent parameters may more accurately decode kinematics and could pave the way for more clinically viable neural prosthetics.

Primary Reader: Dr. Nitish Thakor

Secondary Reader: Dr. Sridevi Sarma

Thesis Committee:

Dr. Nitish Thakor (primary adviser, reader),

Department of Biomedical Engineering,

Johns Hopkins University

Dr. Sridevi Sarma (adviser, reader),

Department of Biomedical Engineering,

Johns Hopkins University

Dr. Marc Schieber (adviser),

Department of Neurology, Neurobiology and Anatomy,

University of Rochester Medical Center