Graduate Research Plan Statement

For many years, it has been thought that the central nervous system reduces the number of degrees of freedom to a smaller number of control variables to solve the inverse kinematics and inverse dynamics problems\(^1\). The research I propose will examine how the human neuromuscular system functions in spaces of reduced dimensionality to execute motor tasks.

The muscle synergy model for the neural basis of movement: There is evidence for the theory of muscle synergies, which suggests that human movement occurs through selective activation of coordinated muscle groups\(^2\). The existence in frogs\(^3\) and rats\(^4\) of spinal modules, in which collections of interneurons stimulate particular patterns of muscle activation, suggests that human movement is similarly controlled in the spinal cord in a modularized manner\(^5\). Muscle synergies are these modularized patterns of muscle co-activation recruited by the cortex. Much is understood about muscle synergies and their ability to reduce dimensionality in the muscle activation space for reaching tasks.\(^2\) However, little is understood about how the cortex selectively activates these muscle synergies to achieve manipulation goals. In the proposed research, I will investigate how population activity in the primary motor cortex (M1) relates to the activation of particular muscle synergies throughout reaching tasks.

The cortical recruitment of muscle synergies: Traditional methods in the study of motor control analyze single neuron properties in M1 and their tuning for particular movement parameters such as reach direction or velocity\(^6\). However, there has been a recent paradigm shift in various fields of neuroscience from the single neuron representational framework towards population level analyses through dimensionality reduction techniques\(^7\). Population level analyses use dimensionality reduction to represent the activity of many neurons as low-dimensional neural states. Using this framework, recent studies have shown that the population activity may be described as a dynamical system\(^8\). In this view, single-neuron responses express aspects of the population dynamics, however viewing these neurons in isolation can lead to confusing or misleading interpretations of neural activity. Particularly, in 2007, a study was conducted analyzing the preferred muscle synergy of single neurons in the M1 of monkeys

This work revealed heterogeneity in the tuning of neurons, failing to show that single neurons in the motor cortex recruit particular muscle synergies.

**Hypothesis:** My proposed research project will investigate the hypothesis that the primary motor cortex functions as a dynamical system to produce particular co-modulation patterns in neurons that project to the spinal cord, which in turn decodes these co-modulation patterns from the motor cortex to compute activation of muscle synergies. In the dynamical systems view, it has recently been shown that there are rotations of the neural state directly following motion onset. These rotations in neural state represent the quasi-oscillatory firing patterns of co-modulated neurons during reach execution. I further hypothesize that this rotation in neural state facilitates the bursting of muscle synergies, which has been observed during reaching tasks.

This research project will work towards a clearer understanding of the neural basis of movement.

**Methods:** A multi-electrode array will be used to record neural activity in M1 of monkeys, while EMG electrodes will be used to record muscle activity during center-out reaching tasks to evenly spaced targets around the periphery. Dimensionality reduction methods will be used to extract each monkey’s muscle synergies and neural co-modulation patterns over all trials. Then on a single trial basis, we will compute correlations in the temporal activation of co-modulation patterns in the neural data and the temporal activation of muscle synergies in the EMG recordings while accounting for communicative delay. Further, we will select muscle synergies with bursting activation during reach execution, and compute correlation between the activation of these muscle synergies and the activation of neural state components with rotational structure during reaching. Correlation significance will be evaluated using statistical permutation tests.

**Intellectual Merit:** Primarily, this work can lead to significant advancements in the study of human motor control. For many years, groups have studied the use of low-dimensional muscle synergies, and there has been increasing evidence of the usefulness of a dynamical systems interpretation of neural activity. However, there is an absence in the literature of how the neuromuscular system functions in both of these reduced spaces to produce timely and reliable movement. For my proposed research project, a model of communication between these reduced spaces will be tested to advance the understanding of human motor control.

**Broad Impacts:** Understanding the neural basis of movement is important for restoring function for paralyzed patients. Over the past decade, there have been significant advancements in motor cortex decoding methods to control neural prostheses. This study will work to reveal the underlying neural mechanisms involved in neuromuscular control to enable higher sophistication in neuroprosthetic control. Additionally, this research can contribute to post-stroke motor rehabilitation methods guided by muscle synergy restoration. Understanding how the cortex recruits muscle synergies can offer an explanation for the high success variability of muscle synergy restoration based motor rehabilitation methods.

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