

Neural Circuit Models to Study the Role of the Spinal Cord in Control of Arm Movement

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Most spinal motoneurons receive relatively weak direct input from the motor cortex, which projects mostly to spinal interneurons that also receive information from somatosensory receptors. These spinal interneurons have patterns of connectivity that allow them to coordinate the various muscles into synergistic and antagonistic relationships that depend on the nature of the intended motor task. We have previously modeled a 2-axis, 4-muscle wrist joint with realistic musculoskeletal mechanics and proprioceptors (spindle primary and GTO afferents) and a network of spinal circuitry based on the classical types of interneurons (propriospinal, monosynaptic 1a-excitatory, reciprocal 1a-inhibitory, Renshaw inhibitory and 1b-inhibitory pathways) and their supraspinal control (via biasing activity, presynaptic inhibition and fusimotor gain). The model replicated realistic properties for a wide range of well-described behaviors such as resisting external force perturbation, tracking position and force trajectories and adaptation to viscous curl force fields. Furthermore, details of stability and temporal patterning of muscle recruitment were surprisingly realistic. In fact, these behaviors appear to be robust emergent properties of the complete set of spinal circuitry as modeled.

We have also completed the groundwork for a spinal cord model that mediates planar arm motion to investigate its role in movement of more complicated musculoskeletal systems. The musculoskeletal model of the arm involves separate, hinge-like elbow and shoulder joints, a common experimental configuration. Each joint is operated by a pair of monoarticular antagonist muscles that provide flexion and extension torque. In addition to these four muscles, the model also includes two biarticular muscles, one providing flexion and the other extension torques across both joints. Based on an extensive literature study on the spinal circuitry, kinetics, kinematics and EMG patterns associated with this movement, we concluded that the monoarticular muscles should be modeled as having an antagonist relationship with the monoarticular muscle crossing the same joint and partial synergist relationships, which include both antagonist and synergist spinal circuits, with the rest of the muscle set. The biarticular muscles should be modeled as having partial synergist relationships with the entire muscle set. These relationships are embodied in patterns of connectivity and associated gains for the five classical spinal pathways. If all of these gains are variable, the arm model would have to optimize 404 parameters, as compared to 200 for the wrist model.

Despite the very large number of gains that must be set in the wrist model, gradient descent methods from random starting values converged rapidly on desirable solutions. Interestingly, similarly good performance was often produced by quite different solutions, suggesting that the interneurons provide a rich set of generally desirable and easily discoverable states for learning new tasks. We are just now exploring whether at least some of these learned gains can be fixed across tasks, reducing what would otherwise be an exponential increase in the dimensionality of systems with more joints and muscles. Our general hypothesis is that the highly conserved spinal circuitry of mammals substantially transforms the properties of the musculoskeletal system that the brain must learn to control in order to perform voluntary movements.