

A neurocomputational model of reaching movements

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Abstract

How the brain controls movement is a question that has fascinated researchers from different areas as neuroscience, robotics and psychology. To understand how we move is not only an intellectual challenge, but it is important for finding new strategies for nursing people with movement diseases, for rehabilitation and to develop new robotic technology.

While there is an agreement about the role of the primary motor cortex (M1) in the execution of voluntary movements, it is still debated what (and how) is encoded by the neural activity of the motor cortex.

To unveil the "code" used for executing voluntary movements we investigated the interaction between the motor cortex and the spinal cord, the main recipient of the descending signals departing from M1 neurons. In particular, the research presented in this thesis aims at understanding how primary motor cortex and spinal cord cooperate to execute a reaching movement, and whether a modular organization of the spinal cord can be exploited for controlling the movement.

On the basis of physiological studies about the primary motor cortex organization, we have hypothesized that this brain area encodes both movement's parameters and patterns of muscle activation.

We argue that the execution of voluntary movements results from the cooperation of different clusters of neurons distributed in the rostral and caudal regions of primary motor cortex, each of which represents different aspects of the ongoing movement. In particular, kinetic aspects of movement are directly represented by the caudal part of primary motor cortex as activations of alpha motoneurons, while kinematic aspects of the movement are encoded by the rostral region and are translated by spinal cord interneurons into alpha motoneurons activation. The population of cortico-motoneuron (CM) cells in the caudal part of M1 creates muscle synergies for a direct control of muscle activity, useful to execute highly novel skills that require a direct control of multijoint and single joint movements by the central nervous system (CNS). On the other side, clusters of neurons in the rostral M1 are devoted to the activation of different subpopulations of interneurons in the spinal cord organized in functional modules. Each spinal module implements hardwired muscle synergies regulating the activity of a subset of muscles working around one or more joints. The

way a module regulates the muscles activations is related to its structural properties. One area recruits the hard-wired motor primitives hosted in the spinal cord as spatiotemporal synergies, while the other one has direct access to the alpha motoneurons and may build new synergies for the execution of very demanding movements. The existence of these two areas regulating directly and indirectly the muscle activity can explain the controversy about what kind of parameter is encoded by the brain.

In order to validate our conjecture about the coexistence of an explicit representation of both kinetic and kinematics aspects of the movement, we have developed and implemented the computational model of the spinal cord and its connections with supraspinal brain. The model incorporates the key anatomical and physiological features of the neurons in the spinal cord (interneurons Ia, Ib and PN and Renshaw cells, and their interconnections). The model envisages descending inputs coming from both rostral and caudal M1 motor cortex and cerebellum (through the rubro- and reticulo-spinal tracts), local inputs from both Golgi tendon organs and spindles, and its output is directed towards alpha motoneurons, which also receive descending inputs from the cortex and local inputs from spindles. The musculoskeletal model used in this study is a one degree-of-freedom arm whose motion is restricted to the extension/flexion of the elbow. The musculoskeletal model includes three muscles: Biceps Short, Brachialis and Triceps Lateral.

Our simulations show that the CNS may produce elbow flexion movements with different properties by adopting different strategies for the recruitment and the modulation of interneurons and motoneurons. The results obtained using our computational model confirm what has been hypothesized in literature: modularity may be the organizational principle that the central nervous system exploits in motor control. In humans, the central nervous system can execute motor tasks by recruiting the motor primitives in the spinal cord or by learning new collections of synergies essential for executing novel skills typical of our society.

To get more insights about how brain encodes movements and to unveil the role played by the different areas of the brain we verified if the movement generated by our model satisfied the trade-off between speed and accuracy predicted by the Fitts' law. An interesting result is that the speed-accuracy tradeoff does not follow from the structure of the system, that is capable of performing fast and precise movements, but arises from the strategy adopted to produce faster movements, by starting from a pre-learned set of motor commands useful to reach the target position and by modifying only the activations of alpha motoneurons. These results suggest that the brain may use the clusters of neurons in the rostral M1 for encoding the direction of the movement and the clusters of CM cells in the caudal M1 for regulating the tradeoff between speed and accuracy.

The simulation performed with our computational model have shown that the activation of an area cannot exclude the activation of the other one but, on the contrary, both the activations are needed to have a simulated behaviour that fits the real behavior.