Modeling the spinal cord neural circuitry controlling cat hindlimb movement during locomotion

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Abstract

The spinal cord neural circuitry was modeled as a network of interacting neuronal modules (NMs). Each NM includes a network of alpha-motoneurons, Renshaw, Ia and Ib interneurons, and interneurons associated with the central pattern generator (CPG). The CPG was integrated with reflex circuits. Each of two three-joint hindlimbs was actuated by 9 one- and two-joint flexor and extensor muscles. The objective was to find the network architecture within and between the NMs that provides stable locomotion with different gaits, realistic patterns of muscle activation, and limb movement kinematics. The results of modeling are discussed in the context of experimental data on cat locomotion.

Summary

We have developed a special simulation package that allows simultaneous modeling of neural circuitry in the spinal cord, involved in neural control of limb movement, and limb biomechanics. The package was used for computational modeling of neural control of cat hindlimb movement during locomotion. The objective was to find (and hence to hypothesize) the architecture of synaptic interconnections within the spinal cord circuits and the schematic of proprioceptive feedback which together provide: (1) stable locomotion with different gaits, (2) realistic patterns of muscle activation, and (3) realistic kinematics of movement.

The neural model of the locomotory CPG was constructed using the hypothesis that each limb is controlled by one complex CPG, which in turn is connected with the other CPGs via a coordinating neural network. The CPG was incorporated into the spinal cord neural circuitry and integrated with the circuits of spinal reflexes via direct synaptic interconnections and through multiple (proprioceptive) feedbacks.

The exact network of interneurons in the mammalian spinal cord that generates the basic locomotor rhythm has not been identified yet. Therefore, in addition to the existing data on the spinal cord neural architecture, we used evidence that the mechanism for the locomotor pattern generation in the spinal cord is functionally similar to the brainstem mechanisms providing generation and control of the respiratory motor pattern (Orlovsky et. al., 1999). Specifically, we suggested that some general architectural principles and particular neural schematics discovered in studies of the respiratory CPG (e.g. those for phase transitions) might be useful and applicable for the construction of the locomotory CPG. In respect to the respiratory CPG, both experimental

(Richter, 1996) and modeling (Rybak et al., 1997) studies have demonstrated that, in addition to the "principal" CPG elements (whose activity explicitly defines each phase of the cycle), the CPG may contain special "switching" neural elements that fire during phase transitions and, in fact, produce these transitions via inhibition of the corresponding principal CPG elements. Importantly, these switching interneurons usually operate (fire) under control of various proprioceptive and descending control signals. The switching interneurons significantly contribute to the generation and shaping of the output motor pattern (timing of phase transitions, shaping firing busts, etc.). Moreover, the switching interneurons adjust the generated motor pattern according to the system/behavioral needs.

The developed model of the spinal cord neural circuitry has a modular structure and has been constructed as a network of Neuronal Modules (NMs). Each NM is considered as a minimal network structure necessary for integration of basic reflexes with the CPG. Each NM controls one muscle and includes an output alpha-motoneuron (alpha-Mn), providing activation to the controlled muscle, and several interneurons, including the Renshaw cell (R-In), Ia interneuron (Ia-In) receiving Ia proprioceptive feedback, Ib interneuron (Ib-In) receiving force-dependent Ib proprioceptive feedback, and two interneurons associated with the locomotory CPG. The CPG elements within NM include the principal CPG neuron (CPG-N) providing activation to alpha-Mn and the switching interneuron (CPG-In) controlling the principal CPG neuron. The entire neural circuitry for control of locomotion comprises a network of NMs (interconnected directly and via proprioceptive afferents). In its turn, the CPG for each limb is formed as a network of all CPG elements located in all participating NMs. The direct synaptic connections within and between the NMs and the "classical" structure of Ia and Ib proprioceptive afferents provide for the classical flexor and extensor stretch reflexes. The CPG is activated by descending drive to the principal CPG neurons (CPG-Ns). Switching the locomotor phases is initiated by the firing of the corresponding "switching" CPG interneuron (CPG-In). The CPG-Ins receive multiple afferent inputs (descending, Ia, Ib, cutaneous, etc.) and control the timing of phase transitions providing adjustment of the duration of locomotor phases (and hence the gait) to "the current behavioral needs".

Interestingly, during the extension phase of locomotion ("stance"), the active extensor CPG-N neuron inhibits the extensor Ib neuron (Ib-In) and hence breaks the "classical" negative feedback loop of Ib fibers to the extensor alpha-motoneurons. At the same time, the same extensor CPG-N neuron receives input from Ib fibers and provides excitation of the extensor alpha-Mn. Therefore during locomotion the Ib feedback loop to the extensor alpha-Mn changes from negative to positive which is consistent with the existing experimental data on cats (Pearson, 1993; Prochazka et. al., 1997).

The developed model has been adjusted for control of locomotor movement of three-joint cat hindlimbs through nine one- and two-joint flexor and extensor muscles. Our simulations have demonstrated that the model can provide a stable locomotion and flexibility necessary for the adaptive adjustment of locomotor movement (gait) to the environment and the goals of movement.