Talk 103

Modeling and Analysis of Neuronal Circuits for Locomotion with Sensory Feedback

(NINDS R01-NS046057 FY 02)

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The broad aim for this project is to enhance the understanding of biological information processing mechanisms. The immediate goals are to uncover the fundamental roles of sensory feedback mechanisms in the neuronal control of animal locomotion and to establish mathematical models that predict the dynamical behavior of and supply missing information about the biological system. More specifically, the aims are to I) perform biophysical and physiological experiments on leech preparations to collect neuronal and mechanical input/output data needed for quantitative models, II) develop a mathematical model of the neuronal control system for leech swimming that includes sensory feedback, III) predict the effects of sensory feedback through numerical simulations of the model, and IV) test these predictions through physiological experiments on leech preparations. The project develops dynamical models of the leech locomotion control system, consisting of the central oscillator, muscle actuation by motoneurons, body-fluid interactions, and sensory feedback from stretch receptors, through parameter identifications based on experimental observations.

So far a systems-level model of the central oscillator has been developed. The model is shown to correctly capture the relation between the intersegmental phase lags and several crucial parameters including the intersegmental coupling strength and the intrinsic periods of segmental oscillators. A model has also been developed for the passive dynamics of leech longitudinal muscles using the length-tension data from step-length-change experiments, and has been successfully tested against sinusoidal-length-change experiments that mimic muscle activities during swimming. We have determined the pacemaker sensitivity (spike frequency versus membrane potential; F-V relationship) of swim-related motoneurons (MNs), which drive muscle contractions. Through pulse-current experiments (Fig.1), the pacemaker sensitivity is found to be approximately linear over a large range (about 20mV) and is modeled by threshold nonlinearities and a linear transfer function capturing the impulse adaptation. This model explains the clockwise F-V loop observed during fictive swimming (Fig.2). The mechanics of leech body and the surrounding fluid has been modeled using the standard multi-body mechanics and simplified fluid mechanics. With an appropriate muscle contraction pattern, the model is able to “swim” at a reasonable speed (Fig.3).

The models of the central oscillator, body-fluid mechanics, and muscle activation mechanism are to be integrated into the whole swimming leech model through sensory feedback. In addition to the biological data, a theoretical tool, multivariable harmonic balance, will be used to guide the integration process. Insights gained from the proposed research on leech swimming are expected to increase our general understanding of neuronal control systems.

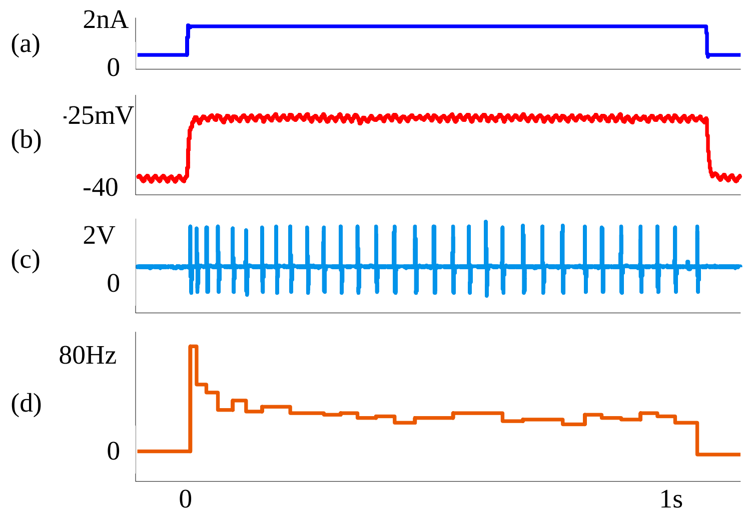

Fig. 1. Relationship between the membrane potential and spike frequency. Current pulses were injected into the soma of MN DE-3 while spike frequency was recorded in the axon of the penetrated cell with extracellular suction electrodes. (a) injected current, (b) membrane potential, (c) extracellular spikes in DE-3 axon, and (d) time course of impulse frequency

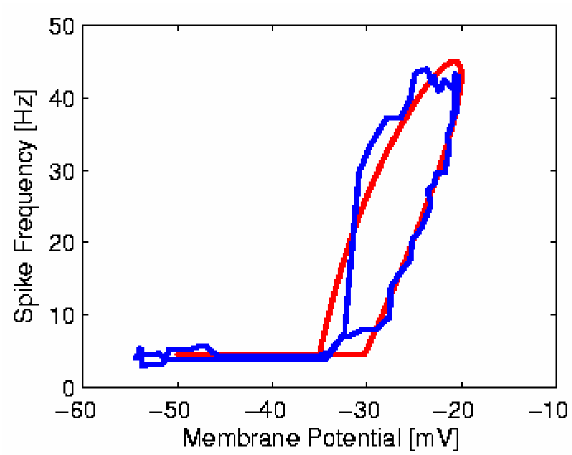

Fig.2: The F-V loops during fictive swimming. Spike frequency (F) versus membrane potential (V) of MN DE-3 obtained when sinusoidal current is injected into the soma. The blue curve is the experimental measurement. The red curve is the prediction by a model that captures the threshold nonlinearity and linear impulse frequency adaptation.

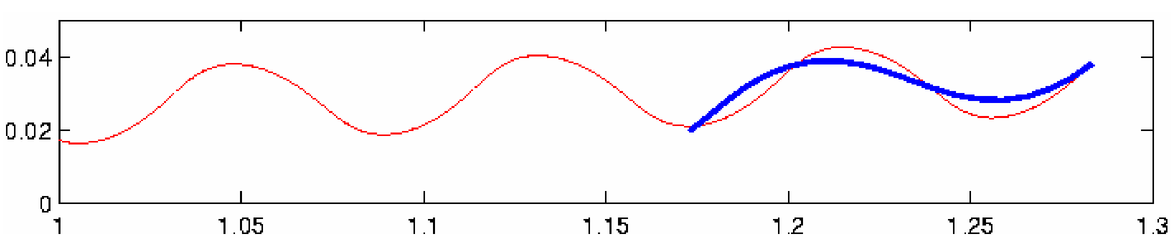

Fig.3: Swimming leech simulated by the body-fluid model. The head trajectory (red) and the snap shot of the leech body at the final time (blue) are shown. The distance of travel over one cycle of undulation, normalized by the wave length, has been experimentally found to be around 0.64 for leeches, whereas the model predicts this value to be about 0.85.

Project Website

http://www.people.virginia.edu/~ti3q

http://www.people.virginia.edu/~wof

Publications

1. T. Iwasaki and M. Zheng, "What makes biological oscillators achieve robust self-excitation?" American Control Conference, 2003.

2. T. Iwasaki and B. Liu, "Feedback control with central pattern generator for decentralized coordination of prototype mechanical rectifier," American Control Conference, 2004.

3. M. Zheng, T. Iwasaki, and W.O. Friesen, "Systems approach to modeling the neuronal CPG for leech swimming," The 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2004.

4. J. Tian, T. Iwasaki, and W.O. Friesen, “Passive properties and model of the leech body wall,” Society for Neuroscience 35th Annual Meeting, November 2005.

5. T. Iwasaki and M. Zheng, “Sensory Feedback Mechanism Underlying Entrainment of Central Pattern Generator to Mechanical Resonance,” Biological Cybernetics, Vol.94, No.4, pp.245-261, April 2006.

6. Z. Chen and T. Iwasaki, “State pattern generation of rectifier systems by circulant neuronal oscillators,” Proc. 17th International Symposium on Mathematical Theory of Networks and Systems, Kyoto, Japan, July 2006 (To appear).

7. Z. Chen and T. Iwasaki, “Exact synthesis of biological pattern generation: a circulant paradigm,” Proc. American Control Conference, Minneapolis, MN, June 2006 (To appear).

8. T. Iwasaki, “Analysis and synthesis of central pattern generators via multivariable harmonic balance,” Proc. American Control Conference, Minneapolis, MN, June 2006 (To appear).

9. M. Zheng, W.O. Friesen, and T. Iwasaki, “Systems-level modeling of neuronal circuits for leech swimming locomotion,” J. Computational Neuroscience (Submitted).

10. Z. Chen and T. Iwasaki, “Circulant synthesis of central pattern generators with application to control of rectifier systems,” IEEE Transactions on Automatic Control (Submitted).

11. Z. Chen and T. Iwasaki, “Analysis and synthesis of weakly coupled oscillators by multivariable harmonic balance approach,” IEEE Conference on Decision and Control, December 2006 (Submitted).

12. J. Tian, T. Iwasaki, and W.O. Friesen, “Static and dynamic components of pacemaker sensitivity in leech,” Society for Neuroscience 36th Annual Meeting, October 2006 (Submitted).

13. J. Tian, T. Iwasaki, and W.O. Friesen, “Passive Mechanical Properties and Model of the Leech Body Wall,” (In preparation).