Phase resetting and dynamic stability of human walking

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Abstract

In the field of motor control, the half-center model, consisting of two half-centers connected mutually by reciprocal inhibition, has played an important role to account for generation of activities of motor neurons innervating antagonist muscles, where one half-center consists of a population of neurons and its activity is responsible for contractions of one group of muscles, while the other half-center for the antagonist muscles [1]. The half-center theory with some extensions for the inter-limb coordination leads to the term central pattern generator (CPG). The term CPG refers to a functional neural network, which could consist of neurons located in different parts of the central nervous system. That is, several centers (i.e., populations of neurons) at different locations are interacting with each other to form a CPG. For the cat, at least one CPG is located in the spinal cord. Moreover, it is assumed that there is one such a center for each limb, and it controls rhythmic movements of that limb [1,2]. Several recent researches have provided observations supporting the existence of human CPGs [2,3]. Although the detailed structure of CPGs in vertebrates is not known, a number of physiological experiments show that the provision of adequate locomotor-related sensory input can activate and regulate the spinal locomotor circuitry including CPGs [2,4]. That is, oscillatory activities of CPGs during locomotion are under continuous influences of the regulatory sensory input. Such regulations are thought to be crucial to maintain the stability of walking. Less studied, however, has been a theoretical foundation for these sensory regulations. In this study, we try to provide a basic theory for these regulations. To this end, we consider a model of musculo-skeletal system controlled by a CPG. In the model, the CPG is simply modelled by a nonlinear limit cycle oscillator, although we are not aware of the plausibility of this simple modelling. We further assume that the CPG produces a desired periodic motion trajectory during locomotion. The musculo-skeletal system is modelled by a double pendulum. A feedback and feed-forward controllers are adopted for the double pendulum to realize the desired trajectory. Then we study responses of the model to impulsive mechanical perturbations applied to the pendulum. The model includes a mechanism that can reset the oscillation phase of the CPG based on the pendulum's state which is fed back to the CPG, leading to the phase reset of the entire-system's state. Several models with different phase resetting mechanisms are considered, and dynamics of each model is compared with that of a model without the phase resetting mechanism. We show that the phase resetting mechanism can improve the response characteristics of the control systems to the external perturbation. That is, it can expand the basin of attraction of the periodic motion and reduce the transient duration of the dynamics necessary for re-establishing the desired trajectory from the perturbed state. Finally, we discuss this result in relation to phase resetting curves observed during human locomotion.

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