Doctoral Dissertation (要約)

Modeling of human stance postural control through musculoskeletal forward dynamics simulation

(順動力学シミュレーションによる
人間の立位姿勢制御モデリング)

by

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Stance postural control, which allows individuals to maintain an upright stance, is one of the most important and basic requirements for a comfortable life. Specifically, human postural control is defined that the neural controller elaborately maintain the human body in a stance posture by coordination of muscles. To understand the mechanism of stance postural control, proposal of neural controller model to exhibit the salient features of human stance behavior through musculoskeletal forward dynamics simulation is important.

Most previous literature used an inverted pendulum without muscles to represent human body, which is not physiologically plausible. In addition, inverse dynamics simulation was used to identify the hypothetical neural controller models based on experimental data. The method only reproduce the experimental data and cannot prove whether or not the proposed neural controller model is correct. Modeling human postural control by musculoskeletal forward dynamics simulation is necessary.

In this thesis, neural controller models are proposed to understand three problems for human postural control as follows:

(1) How the neural controller compensates the neurological time delay during the unperturbed stance.
(2) How the neural controller regulates the muscle stiffness level under different sensory input conditions during the unperturbed stance.
(3) How the neural controller counters the perturbations during perturbed stance.

For (1), we hypothesized that the neural controller model consisting of feed-forward control and feedback control can compensate a 120ms neurological time delay, which is a plausible delay latency. Specifically, feed-forward control is defined as a set of necessary muscle activations to maintain a musculoskeletal model in a stance posture. The variables in the controller are designed by optimization-based method to keep musculoskeletal model stably. The hypothesis is physiologically plausible from two aspects. Firstly, the neural controller can successfully compensate the neurological time delay. Secondly, comparing with experimental data of muscle activations for human quiet standing, we find that the neural controller can simulate muscle activations that fall within the most of activation ranges of experimental data, indicating that the neural controller model is plausible. Further, the simulated muscle activations reflect the feature human will select a relative low muscle stiffness level for low energy consumption when standing freely.

For (2), we hypothesized that when sensory input condition changes, human increase the muscle stiffness level but at a minimal energy consumption cost to compensate sensory loss. We propose a neural controller model incorporating multisensory inputs under unperturbed stance condition. A 120-ms delay is considered, as well. The variables in the controller are designed by optimization method to minimize the energy consumption for keeping musculoskeletal model standing stably under four different sensory input conditions. Compared with experimental data of the change of muscle activations respect to four corresponding sensory input conditions, simulated results exhibit the increase of muscle activation level when one or two sensory inputs get lost. The hypothesis is physiologically plausible because the features exhibited by simulated data coincides with the physiological knowledge that individuals might stiffen their body during upright standing to cope with the deterioration in sensory input.

For (3), we hypothesized that a proper feedforward input with a feedback control can maintain the balance of the musculoskeletal model under perturbations by proper postural strategy. We propose a neural controller model incorporating multisensory inputs under perturbed stance condition. The perturbation is modeled as the backward movement of an altered platform. A proper feedforward input is firstly selected. Then, the variables of the feedback control are designed to keep the musculoskeletal model standing under different perturbation magnitudes. The hypothesis is physiologically plausible because the simulated result exhibit an ankle strategy to counter the small perturbations.

In sum, neural controller models which exhibit several salient features of human stance behaviors are proposed. The simulation and optimization framework for musculoskeletal forward dynamics simulation is constructed. These can be the foundation of the further quantitative investigation on human postural control mechanism.