Postural control mechanism of human bipedal standing

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Bipedal standing is one of the fundamental behaviors in human being, and the understanding of its control mechanism and stability is essential for the quality of life of the elderly and the improvement of sport performances. The understanding of the relationship between body fluctuations and muscle activities during quiet standing will enhance the knowledge of the human body controller in the central nervous system, and yet it has not fully understood due to the aperiodicity and nonlinearity of the body sway and small muscle activities. In this dissertation, I investigated the postural control mechanism and postural stability from the aspect of biomechanics (in vivo) and bioengineering (in silico).

In STUDY 1, 2, and 3, I investigated the coordinative structure of kinematics and muscle activities during tiptoe standing. In STUDY 1, I compared joint coordination during tiptoe standing between ballet dancers and non-dancers to investigate the change in kinematic coordina-

tive structure through balance training. Joint coordination was calculated by using principle component analysis and the ankle-knee coordination in the sagittal plane showed in-phase coordination for ballet dancers while non-dancers showed its anti-phase coordination. This study indicated the plasticity of joint coordination through training and the possibility that joint coordination reflects balance stability during standing. Then I investigated the relationship between joint coordination patterns and muscle co-activation in STUDY 2. The surface electromyograms (EMG) over 13 leg muscles were recorded together with kinematic data, which was used for the calculation of joint coordination in the same way as STUDY 1. I found that in-phase coordination, which was the feature of joint coordination in ballet dancers in STUDY 1, was associated with EMG-EMG coherence (muscle co-activation) up to 50 Hz, while anti-phase coordination was not associated with muscle co-activation in such a high frequency band. The relationship between kinematics and kinetics coordination was proved for the first time in this study. Moreover, I investigated the relationship between joint phase transition in a short period and muscle activations in STUDY 3. The joint phase transition (joint coordination) was computed by using the Hilbert transformation in this study. I observed the cross correlation between phase transitions and EMG signals, suggesting that short periods of phase transitions is controlled via muscle activities.

In STUDY 4 and 5, I investigated the function of intermittent feedback control for human bipedal standing in silico (STUDY 4) and in vivo (STUDY 5). In STUDY 4, I implemented computer simulation of a quadruple inverted pendulum as a model of human tiptoe standing. I set an intermittent feedback PD controller with joint viscoelasticity and joint control strategy (intermittent, continuous, or passive) as simulation parameters. First, I confirmed that the joint fluctuations of the pendulum showed similar properties as the actual human body oscillations during tiptoe standing. Among the 480 pairs of simulation parameters, I found only 30 pairs that can stabilize the pendulum for more than 60 seconds, in which the hip must always be controlled intermittently. Also, postural robustness of the pendulum varied with different joint control strategies, which accompanied with the change in kinematic joint coordination. This study showed the necessity of intermittent feedback controller for the postural control during quiet standing of multi-segment human body. However, the function of intermittent control regarding muscle activities has not yet been understood at all. So in STUDY 5, I investigated intermittent muscle activity during quiet standing in vivo. Kinematic and kinetics (EMG) data were recorded to analyze the EMG on/off switch timing in the phase plane and the contribution of EMG on/off switching to control output (that is, joint torque). Both EMG on and off periods were distributed in the first and third quadrant of the phase plane where unstable manifolds of the system are considered to exist. In addition, the EMG on/off switching was associated with joint torque fluctuations along with anatomical direction of action for each muscle. This is the first study to demonstrate the function of intermittent muscle activations towards the control output.

In summary, I found various evidences regarding postural control structure at musculoskeletal level, its function, and expertise (or plasticity) of postural control mechanism. This dissertation deepened the understanding of postural control mechanism in which the control system selects suboptimal control strategy among the redundant system for stabilizing the body in a constantly changing environment.