Digest of thesis

Muscle and kinematic coordination system in human walking

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A thesis submitted for the degree of
Doctor of Philosophy
(Human and Environmental Studies)

The most popular locomotion for human is walking, which does not require intensive control. Although walking seems to be achieved effortlessly, control of walking is difficult because the human musculoskeletal system is constructed by over 400 muscles or over 200 bones. We can easily expect that it is so complicated to control huge number of muscles or joints at appropriate timing. However, humans seem to construct a control system in the central nervous system (CNS) to control huge number of muscles or joints. In fact, we can coordinate muscles or joints during walking in daily life. Moreover, walking has flexible adaptability. For example, we can adapt unstable surfaces or obstacles effortlessly. Robotics technology has developed day after day, however, there is no adaptable bipedal robot that includes huge number of degrees of freedom as much as humans. This means that the control of large degree of freedom is extremely difficult, and controlling system that coordinates large degree of freedom has been an open question. Considering this, it is astonishing that the CNS coordinates large degrees of freedom during walking. My motivation of this thesis is to identify astonishing control system that the CNS coordinates numerous muscles or joints during walking.

To control a musculoskeletal system that has redundant degrees of freedom, the

CNS must coordinate numerous muscles of the musculoskeletal system. It has been revealed that the main features of muscle activity patterns could be described by a few underlying components. As a building block of low-dimensional control, the concept of muscle synergy, which simplifies the control of muscles by modularly organizing several muscles, has been proposed. In human walking, it has been revealed that sets of extracted muscle synergies characterize muscle patterns of specific phases of the gait cycle (e.g., the loading response phase, late stance phase or the swing phase). A muscle synergy is constructed by weightings, which denote how the CNS distributes weighting of command to each muscle and its coefficients, which indicate activation timing and amplitude of a muscle synergy. Similar to the muscle synergy, groups of simultaneously moves segments (intersegmental coordination) and their activation patterns (temporal coordination) have been investigated as kinematic synergies using the matrix factorization technique. Previous studies showed the muscle synergy characteristics depended on the biomechanical outputs. This might indicate that characteristics of muscle synergies or kinematic synergies depend on how the CNS plans the desired walking motion. In such control system, I can describe the system that biomechanical outputs of walking (e.g. walking speed, muscle activity, and stride time-length combinations) were generated via muscle synergies or kinematic synergies. I supposed that investigating how the muscle synergies or kinematic synergies depend on the biomechanical factor contributes to identification of coordination of muscles or joints. Then, the purpose of this thesis was to identify the flexible coordination system during walking by the muscle synergy and kinematic synergy analysis.

In order to investigate how the biomechanical factor influences the muscle/kinematic synergies, I needed to select effective biomechanical factors. I selected walking speed, ageing, stride time-length combinations, and surface condition as the biomechanical factor. At first, walking speed is the most common factor for changing the walking. In *Study-1*, I investigated how the activation of muscle synergies depend on walking speeds using the center of activity (CoA) that indicates the center of the distribution of activation timing within one gait cycle. Ten healthy men walked on a treadmill at 14 different walking speeds. I measured the surface electromyograms (EMGs) and kinematic data. Muscle synergies were extracted using non-negative matrix factorization. Then, I calculated the CoA of each muscle synergy activation. As a result, I observed that the CoA of each specific synergy would shift as the walking speed changed. This shifting of the CoA indicates that the CNS controls intensive activation of muscle synergies during the regulation of walking speed. I concluded that the CNS flexibly controls the activation of muscle synergies in regulation of walking speed in *Study-1*. As an extensive analysis for *Study-1*, I investigated the local dynamic stability and orbital stability of activations of muscle synergies across various walking speeds using maximum Lyapunov exponents and maximum Floquet multipliers in *Study-2*. Maximum Lyapunov exponents quantify how the system's states respond to very small local perturbations continuously. On the other hand, maximum Floquet multipliers quantify the tendency of the system's states to return to the periodic limit cycle orbit after small perturbations. In summary, local dynamic stability is quantified by the short-term maximum Lyapunov exponents, and orbital stability is quantified by the maximum Floquet multipliers. I revealed that the local dynamic stability in the activations decreased with acceleration of walking speeds. I concluded that the local dynamic stability in the activation of muscle synergies decrease as walking speed accelerates. On the other hand, the orbital stability is sustained across walking speeds in *Study-2*. In *Study-3*, I investigated characteristics of muscle synergies in elderly adults as an applied research. I measured electromyograms of the lower limb in young and elderly adults during treadmill walking at the personal preferred speed to show how ageing-related neuromuscular dysfunctions affect muscle synergies and their activation. Computation of the maximum Lyapunov exponents of muscle synergy activation and clustering of muscle synergies were performed. I found that muscle synergy constructions were similar between young and elderly adults, and local dynamic stability in muscle synergy activations were not different between young and elderly adults during preferred walking speeds. These results suggest that muscle synergy construction was invariable, and elderly adults might walk slowly to maintain of walking stability. As well as the muscle synergies, characteristics of kinematic synergies were investigated in *Study-4* and *Study-5*. In *Study-4*, I investigated the stability of kinematic coordination during walking across various stride time-length combinations. The whole body kinematic coordination has been quantified as the kinematic synergies that represents the groups of simultaneously move segments (intersegmental coordination) and their activation patterns (temporal coordination). I revealed the maximum Lyapunov exponents were high at fast walking speeds and very short stride length conditions. This implies that fast walking speeds and very short stride length were associated with lower local dynamic stability of temporal coordination. I concluded that fast walking was associated with lower local dynamic stability of temporal coordination of kinematic synergies in *Study-4*. Because flexible adaptability is one of an important characteristics of walking, I investigated modulation of kinematic synergies during adaptation to reveal control system for whole body coordination through adaptation process in *Study-5*. I extracted kinematic synergies during slacklining and ground walking by using the singular value decomposition to investigate changes of whole body kinematic coordination during adaptation. I observed that the kinematic synergies were similar through the adaptation to the slackline, and I also found the kinematic synergies were similar among slacklining and ground walking conditions. This indicates that the whole body kinematic coordination patterns were consistent during the adaptation, and this patterns underlie the universal gait. I concluded that the whole body kinematic coordination is consistent during adaptation to bouncing narrow road.

In summary, my motivation of this thesis was to identify control system that the CNS coordinates numerous muscles or joints during walking. I investigated how modulation of biomechanical factors affect characteristics of muscle/kinematic synergies. I revealed many consistent muscle or kinematic synergy constructions in various conditions (changing walking speed, changing stride time-length combination, ageing, and adaptation). Moreover, I found center of activity or local dynamic stability of activation pattern of muscle/kinematic synergies depended on the kinematic factors. These results indicate that temporal patterns of muscle/kinematic synergies were modulated with changing biomechanical outputs, on the other hand, spatial patterns of muscle/kinematic synergies were consistent. This consistent spatial patterns might contribute to output invariable walking motion pattern, and flexible temporal patterns might contribute to flexible control of biomechanical outputs. I concluded that muscle synergies and kinematic synergies are fundamental system for coordination of musculoskeletal system in human walking. Humans might be constructing a control system that flexibly adjust universal spatial patterns of synergies in accordance with a situation, and such control system might significant role in achieving highly adaptable walking.