Muscle Synergies of Sit-to-Stand and Walking Account for Sit-to-Walk Motion

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In daily lives, humans do not always perform a single motion separately, but they adequately transit their motions to achieve complex movements. Although human sit-to-stand and walking motions are reported to be explained from the small number of modules (called synergy), it has not been revealed how the transit motion (sit-to-walk) is achieved. This study conducted an experiment to measure body trajectory, reaction force and muscle activation of one healthy participant during sit-to-stand, walking and sit-to-walk motions. Results showed that muscle activation during sit-to-walk motion could be explained from the muscle synergies of sit-to-stand and walking. Moreover, it was implied that each muscle synergy needed to be activated adaptively in order to generate momentum and successfully initiate the first step.

1 Introduction

Recently, many elderly people have been suffered from declined physical ability. In order to solve the situation, it is necessary to understand how humans perform the movement. To date, we have focused human sit-to-stand motion which is an important daily activity. In sit-to-stand motion, humans have to control their redundant muscles to move their joints. Our previous study implied that four sets of modules (called msucle synergy) could explain most amount of observed muscle activation during sit-to-stand motion [1].

However, in daily lives, humans adequately transit their motions rather than performing a single motion separately. Especially, humans usually do not only stand up and other activities such as locomotion follow after it. In the previous study, it has been implied that five muscle synergies could explain human voluntary locomotion [2]. However, it has not been clarified whether the same muscle synergies of sit-to-stand and locomotion are applicable to sit-to-walk motion. Moreover, it is unknown how humans coordinate their muscles to achieve the transit movement from sit posture to walk motion. Therefore objective of our study is to clarify muscle synergy structure during sit-to-walk movement.

2 Method

2.1 Muscle Synergy Model

Muscle synergy model has been firstly proposed by Bernstein [3]. Figure 2 shows idea of muscle synergy model [2]. It has two components of spatial pattern $\mathbf{w}$ (Fig. 2 (a)) and temporal pattern $\mathbf{c}$ (Fig. 2 (b)). Spatial pattern indicates relative muscle activation level and temporal pattern represents time-varying weight coefficients of each spatial pattern. In the model, muscle activation (Fig. 2(c)) is assumed to be generated from linear summation of spatiotemporal patterns. In order to extract muscle synergies from muscle activation, nonnegative matrix factorization (NNMF) is used [4].

In this study, firstly, muscle synergies are extracted from human sit-to-stand and walking motions. From previous studies [1][2], the numbers of muscle synergies are determined as four and five for sit-to-stand and walking motion respectively. Next, spatial pattern of these synergies are fixed and temporal patterns are calculated through optimization to minimize squared error from observed muscle activation. In order to validate that muscle synergies of sit-to-stand and walking movement can be used for sit-to-walk motion, coefficient of determination is used for evaluation [5].

2.2 Experiment

Three experimental conditions were tested: sit-to-stand, walking, and sit-to-walk motion. One healthy male participant (23 years old) participated at our experiment. In the experiment, body kinematics, reaction force from hip and feet, and muscle activation were measured using optical motion capture system (MotionAnalysis Corp.; MAC3D), force plates (TechGihan Corp.; TF-4060 and TF-3040) and surface electromyography (S&ME Corp.; DL-142) in 100, 1,000 and 1,000 Hz respectively. The same signal processing procedure was used as the previous study [2]. Ten muscles from lower limb and upper body were measured; tibialis anterior, gastrocnemius, soleus, rectus femoris, vastus lateralis, biceps femoris long head, biceps femoris short head, gluteus maximus, recutus abdominis, and elector spine. Moreover, amplitude of muscle activation data of each trial was normalized based on the maximum activation level of the trial. Ten trials of each condition were used for analysis. During walking and sit-to-walk motion, the participant was asked to start walking from his right feet. The duration 1 s before and 2 s after the hip rising was used for sit-to-stand. When extracting muscle synergy from walking motion, only the duration from the first right heel strike and next one was used. The duration for sit-to-walk trials was from 1 s before hip rising until the second right heel strike.

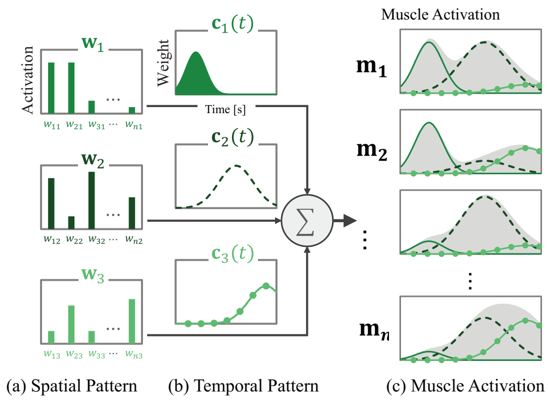

Fig. 1 Muscle Synergy Model

3 Results and Discussion

From the experiment, four and five synergies were extracted from sit-to-stand ($\mathbf{w}^{sts}_{1,2,3,4}$) and walking ($\mathbf{w}^{walk}_{1,2,\cdots 5}$) motions respectively. They had the same characteristic muscle activation as the previous studies [1][2].Using these spatial patterns, temporal patterns were obtained through optimization, and coefficient of determination was 0.89±0.02. This results implied that synergies of sit-to-stand and walking motions could account for most of the muscle activation during sit-to-walk.

Figure 2 shows temporal pattern of synergies. Black solid lines, red dashed lines, green lines with circles show temporal patterns during sit-to-walk, sit-to-stand, and walking respectively. Magenta vertical lines and gray squares show the events of hip rising (HR), the first toe lifting (TL) and right leg stance phase. In sit-to-walk motion, it was found that the synergy $\mathbf{w}^{sts}_1$ did not change. However, the synergy $\mathbf{w}^{sts}_2$ had additional peak during toe lifting in order to initiate walking motion by rising right toe. Synergy $\mathbf{w}^{sts}_3$ ended earlier to stop body extension at the time of toe lifting. Synergy $\mathbf{w}^{sts}_4$ diminished after hip rising but had a different peak during heel strike to control their posture. The synergies $\mathbf{w}^{walk}_{1,2,3}$ started activating earlier around hip rising time in order to extend knee, kick out, and to control upper body. These synergies were supposed to generate momentum for smooth motion transit. The synergy $\mathbf{w}^{walk}_4$ activated in transition phase to move their mass forward. The synergy $\mathbf{w}^{sts}_5$ seems to work periodic regardless of motion transition.

4 Conclusion

This study analyzed human sit-to-walk motion using muscle synergy analysis. Muscle synergies of sit-to-stand and walking motions could explain most of the muscle activation during sit-to-walk motion. Furthermore, it was clarified that temporal patterns of some synergies were adaptively activated ($\mathbf{w}^{sts}_{2,3,4}$ and $\mathbf{w}^{walk}_{1,4}$) or diminished ($\mathbf{w}^{sts}_1$) in order to achieve the sit-to-walk motion.

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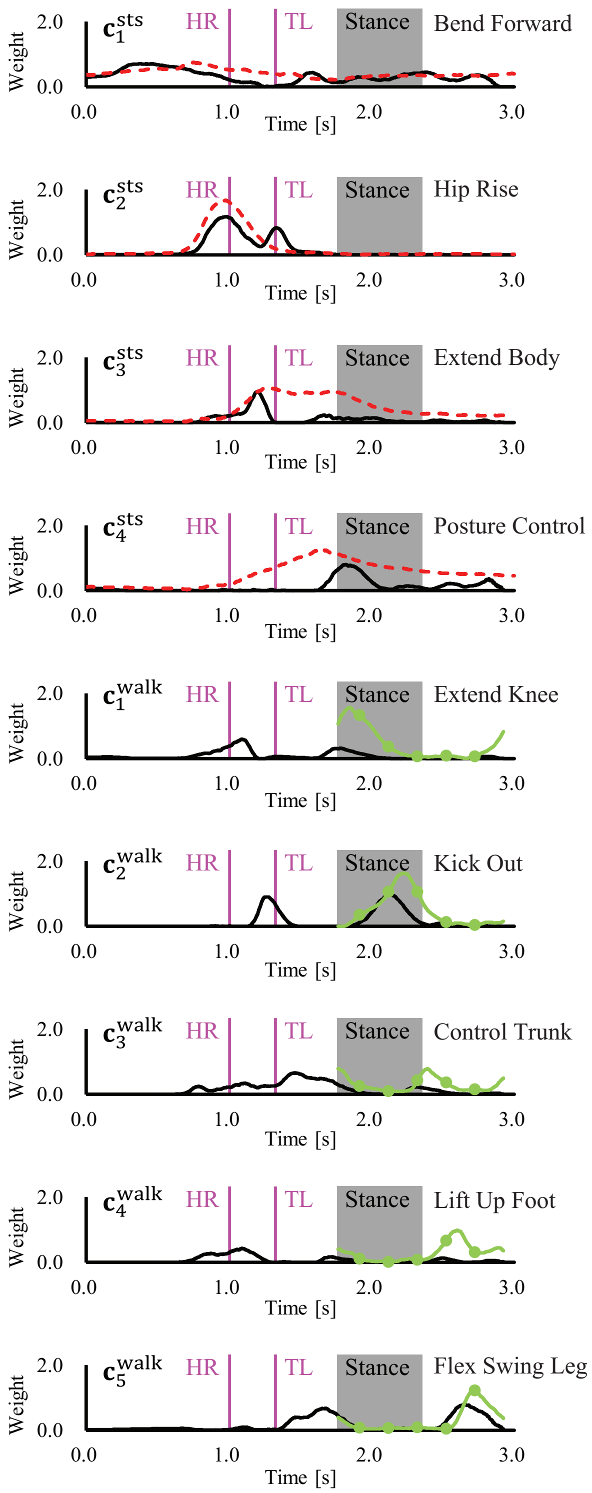

Fig. 2 Temporal Patterns of Muscle Synergies