Different Temporal Structure of Muscle Synergy between Sit-to-Walk and Sit-to-Stand Motions in Human Standing Leg

Qi An, Hiroshi Yamakawa, Atsushi Yamashita, and Hajime Asama

***Abstract*— Humans do not only perform individual motion separately, but they transit motions from one to another. It has been widely known that human sit-to-stand and walking motions are composed of four and five muscle synergies, but it is not clarified how humans utilize these muscle synergies to generate sit-to-walk motion. This study conducted a measurement experiment to identify muscle synergy structure in standing leg during the sit-to-walk motion. Results showed that the same muscle synergy of sit-to-stand and walking could explain sit-to-walk motion. Three of four synergies in sit-to-stand was not significant different but the last synergy was adaptively changed in order to shorten the time of postural stabilization to initiate stepping motion.**

I. INTRODUCTION

HUMANS do not perform individual motion separately, but they adaptively transit motions in daily lives. As shown in Fig. 1, humans can continuously transit one motion (standing-up) to another (walking). Now many elderly people have been suffering from declined physical ability. In order to help and assist them, it is necessary to understand the mechanism to perform transit motion. To this end, it is important to clarify how humans control their redundant muscles. Human body is a redundant system that they have to control more muscles than the number of joints, and it has not been clarified how humans control these redundant muscles.

Our research group has focused on the human sit-to-stand motion (STS) and we found that four sets of synchronized muscle activation (called synergy) could explain human sit-to-stand movement [1]. Another study implied that human locomotion are composed of five modules [2]. Moreover, our previous study [3] implied that human sit-to-walk (STW) motion can be successfully explained by muscle synergies of STS and walking motions. However, the study only focused on the leg which initiated the step and did not consider the other leg (the one remains backward: standing leg). This leg is also important to support the body weight when humans initiate the locomotion. Therefore the purpose of this study is to particularly focus on the standing leg to find whether the standing leg utilize the muscle synergy to support the weight during STW motion. Furthermore, the muscle synergy structure is investigated.

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Qi An, Hiroshi Yamakawa, Atsushi Yamashita, and Hajime Asama are with the Department of Precision Engineering, The University of Tokyo, Tokyo, Japan (e-mail: anqi@robot.t.u-tokyo.ac.jp).

Fig. 1. Sit-to-walk movement. In a daily life, humans do not perform the single activity. They can transit several motions smoothly.

II. METHODS

A. Muscle Synergy Model

Muscle synergy model was firstly proposed by Bernstein which suggested that human complex movement was composed of the limited number of modules (called synergy) [4]. The model usually assumes that muscle activation is generated by the linear summation of spatiotemporal patterns as in the following equation,

$$\mathbf{M} = \mathbf{WC}, \quad (1)$$

where matrices $\mathbf{M}$, $\mathbf{W}$, and $\mathbf{C}$ represent muscle activation, spatial patterns (synchronized muscle activation), and temporal patterns (time varying weighting coefficient). In order to determine spatiotemporal patterns $\mathbf{W}$ and $\mathbf{C}$ from muscle activation $\mathbf{M}$, the non-negative matrix factorization is employed [5]. Figure 2 shows the schematic idea of muscle synergy model. The left graphs show the spatial patterns of muscle synergy and the middle graphs show their time-varying weighting coefficients. Spatial patterns represent relative muscle activation level and it is supposed to be constant. On the other hand, humans need to control their weight to achieve various movement. Linear summation of this spatiotemporal patterns generates muscle activation as shown in the right graphs in Fig. 2.

In order to determine spatiotemporal structure during STW motion, this study performs experiment with healthy participant to measure muscle activation in STS, walking and STW motions. Firstly muscle spatial patterns $\mathbf{W}$ are extracted from STS and walking motions. Next, temporal patterns $\mathbf{C}$ are calculated using optimization procedure for STW motion to minimize the following error z,

$$z = |\mathbf{M} - \mathbf{WC}|^2, \quad (2)$$

when the muscle activation matrix $\mathbf{M}$ during STW and the spatial pattern matrix $\mathbf{W}$ of STS and walking are given. In order to evaluate whether muscle synergies of STW and walking can account for the muscle activation during STW, a coefficient of determination R^2 is calculated.

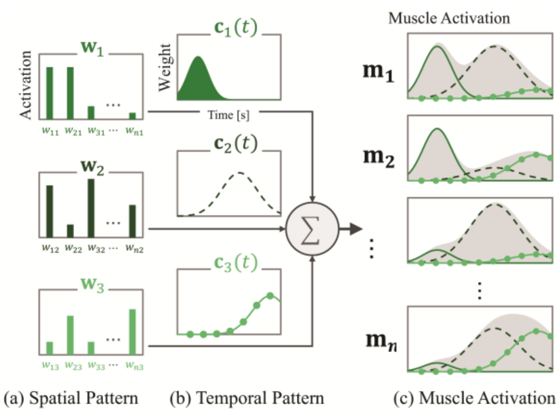

Fig. 2. Muscle Synergy Model. Above figure shows that three muscle synergies generate muscle activation. Muscle activation could be expressed using linear summation of spatiotemporal patterns.

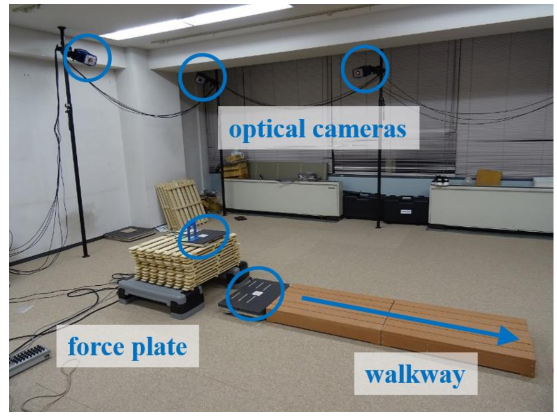

Fig. 3. Experimental setup. Optical motion capture system and force plates are used to measure kinematics and reaction force. Walkway is also prepared to ease walking continuously from sitting posture.

B. *Experiment*

Measurement experiment was conducted to record body trajectory, reaction force from feet and hip, and muscle activation in 100, 1,000, and 1,000 Hz respectively using optical motion capture camera (MotionAnalysis Corp.), force plates (TehGihan Corp.), and surface EMG sensors (Cometa Corp.). Reflective markers are attached to the participant body based on Helen Hayes marker set. Our experiment measured ten muscles which either flex or extend the ankle, knee, hip and lumbar joints: tibialis anterior, gastrocnemius, soleus, rectus femoris, biceps femoris long head, biceps femoris short head, gluteus maximus, rectus abdominis, and elector spine. Muscle data is filtered with the band-pass filter from 60-200 Hz, and the moving average was obtained for 0.5 s before and 0.5 s after the data. In addition, it is normalized based on maximum voluntary contraction. Body trajectory data was filtered with 5 Hz low pass filter and reaction force data was filtered with 20 Hz low pass filter.

In the experiment, three male participant (23.6$\pm$1.2 years old) performed 15 times of three different motion (STS, walking, and STW). During STS condition, participants were asked to stand up from their knee height chair in a comfortable speed. In the walking condition, they started walking motion from the standing posture. In STW condition, they were told to continuously transit their movement from sitting to walking. During all the condition, they were told to cross their arm in front of their chest. All the data was normalized in order to be compared. The start time of STS began at the time when they bended their trunk, and it is end when they stood upright. On the other hand, walking condition started at the second toe lift and finished at the next toe lift. In the STW motion, the start time was decided in the same way as STS movement, and it finished at the second toe lift. Figure 3 shows our experimental setup. The participants firstly sat down on the chair to place their hip and feet onto the forceplate. In the STS condition, they stood up without moving their feet. On the other hand, humans continued to walk in the walkway during STW and walking motions.

III. Results

Firstly four and five synergies were extracted from STS and walking motions. Using the spatial patterns of these nine synergies, 90% of muscle activation during STW could be successfully explained ($R^2 > 0.90$). Focusing on the muscle synergy structure of STS, first three muscle synergies were not significantly different from the original patterns. However, the temporal pattern of the last muscle synergy was ended earlier than the original one. This implies that the participant did not need postural stabilization in STW as much as STS motion.

IV. Conclusion

Spatial patterns of muscle synergies from STS and walking motions could explain muscle activation during STW. However, their temporal patterns were adaptively changed in order to start walking motion and generate initial momentum for locomotion start.

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