Identification of Muscle Synergy Parameters in Different Strategies of Human Standing-up Motion

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概要 Standing-up motion is an important daily activity. It is necessary to understand the mechanism of standing-up motion to improve physical ability of the elderly. This study employed the concept of muscle synergy to clarify how humans coordinated muscle activity to achieve standing-up motion. Muscle synergy model was developed to represent muscle activation that generates standing-up motion. The results showed that different strategies of standing-up motion can be successfully represented by four muscle synergies. In addition, the results showed that the start time, peak time and amplitude are significantly different among the temporal patterns of the two strategies. These characteristics could be used in explaining how humans coordinate different kinds of movements.

キーワード: standing-up motion, muscle synergies analysis

1 Introduction

In the past six decades, the world's elderly population has been sharply increasing. According to the United Nation, the proportion of the world's population aged 60 years or over increased from 8% in 1950 to 12% in 2013, and it will increase more rapidly to reach 21% in 2050 [1]. It is a big burden for society to take care of the elderly in particular due to the high costs of welfare fees. On the other hand, for the elderly, the declined physical abilities make their daily life inconvenient. Data from National Center Health Statistics showed that people over the age of 65 have difficulty in rising from chairs [2]. Moreover, in previous research about functional limitations of the elderly [3], the chair-stand test has been used in the physical performance tests to assess lower body strength. From these studies, standing-up motion is suggested to be an important activity for the elderly, which influences their daily activities. Improving the standing-up motion of the elderly population could then improve their living conditions as well as alleviate the financial burden. Therefore, this paper especially focuses on standing-up motion.

To understand different kinds of standing-up motions, Hughes et al. defined three strategies (momentum transfer, stabilization, and hybrid) that people used in standing-up motion [4]. For the momentum transfer strategy, the subject moves the body upward before moving the center of mass (CoM) on the feet. For the stabilization strategy, the subject moves the CoM on the feet firstly, and then starts to move the body upward. The hybrid strategy is the middle between momentum transfer and stabilization. They found that the elderly tended to use stabilization strategy. However, this study only analyzed kinetic and kinematic parameters. Because muscle activities are associated with human motions, it is necessary to analyze muscle activities to deeply understand how humans generate motions. Doorenbosch et al. used muscle activation of monoarticular and biaticular muscles to explain standing-up motion of two different strategies[5]. Their research indicated that specific muslces activation (Tibialis Anterior, Soleus) were significantly different under two different conditions. Therefore, we can analyze human motions based on both kinematic parameters and muscle activities.

To clarify the standing-up motion based on muscle activities, the muscle synergy theory is employed. The muscle synergy concept was firstly proposed by Bernstein, which suggested that human movements could be generated from a limited number of modules (called synergy) [6]. Previous studies of Ivanenko [7] and Weiss [8] also showed human movements could be explained by a small number of muscle synergies. Their conclusions showed that a number of human motions could be explained by muscle synergies.

Forward dynamic simulation of An [9] showed different coordinative structure could generate the three strategies defined by Hughes [4]. Through simulations, this research found that different strategies could be generated by changing the start time of muscle synergies. However, their study only conducted a simulation study, and it has not validated in measurement experiment. In addition, there might be other important parameters to generate different strategies.

The objective of this present research is to clarify muscle synergy structure in different strategies of human standing-up motion, and find important parameters of muscle synergy to generate different motion strategies.

2 Method

2.1 Muscle Synergy Model

In this study, muscle activation can be expressed as a linear summation of spatial pattern and temporal pattern.

In the Eqs. (1)-(4), $\mathbf{M}$, $\mathbf{W}$, and $\mathbf{C}$ indicate muscle activation matrix, spatial pattern matrix and temporal pattern matrix respectively. N indicates the muscle synergy number and n represent the muscle number. Spatial pattern $\mathbf{W}$ is used to represent the

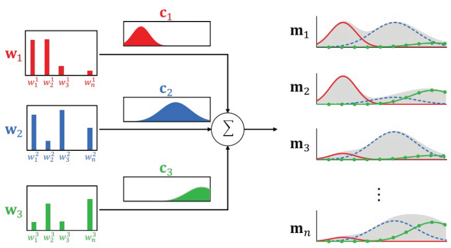


Fig. 1: Muscle synergy model

relative activation level of muscle, and temporal pattern **C** is used to indicate the weighting coefficient of muscle synergy.

Figure 1 shows a schematic design of muscle synergy model. Three muscle synergies are used to express n muscle activations. They are composed of spatial and temporal patterns. Spatial patterns ($\mathbf{w_{1,2,3}}$) show relative muscle activation level. Temporal patterns ($\mathbf{c_{1,2,3}}$) show the relative weighting coefficients. During the motion, spatial patterns are constant, but temporal patterns change according to the time. Muscle activations are generated from linear summation of spatial and temporal patterns of muscle synergies. Muscle activations are shown in gray areas and muscle synergy 1, 2, and 3 are described in red, blue, green lines in Fig. 1. To calculate elements of the matrices **W** and **C**, non-negative matrix factorization algorithm was used [10]. Fistly, the initial elements of matrix **W** are decided randomly. Secondly, the matrix **C** is solved using Eq. (5). Thirdly, the matrix **W** can be solved by Eq. (6). By repeating Eqs. (5) and (6), matrices **W** and **C** can be obtained.

$$\mathbf{M} = \mathbf{WC} \tag{1}$$

$$\mathbf{M} = \begin{pmatrix} \mathbf{m_1}(t) & \mathbf{m_2}(t) & \dots & \mathbf{m_n}(t) \end{pmatrix}^T = \begin{pmatrix} m_1(1) & \dots & m_1(t_{max}) \\ \vdots & \ddots & \vdots \\ m_n(1) & \dots & m_n(t_{max}) \end{pmatrix} \tag{2}$$

$$\mathbf{W} = \begin{pmatrix} \mathbf{w_1} & \mathbf{w_2} & \dots & \mathbf{w_N} \end{pmatrix} = \begin{pmatrix} w_{11} & \dots & w_{1N} \\ \vdots & \ddots & \vdots \\ w_{n1} & \dots & w_{nN} \end{pmatrix} \tag{3}$$

$$\mathbf{C} = \begin{pmatrix} \mathbf{c_1}(t) & \mathbf{c_2}(t) & \dots & \mathbf{c_N}(t) \end{pmatrix}^T = \begin{pmatrix} c_1(1) & \dots & c_1(T_{max}) \\ \vdots & \ddots & \vdots \\ c_N(1) & \dots & c_N(T_{max}) \end{pmatrix} \tag{4}$$

$$\mathbf{W^TWC} = \mathbf{W^TM} \tag{5}$$

$$\mathbf{CC^TW^T} = \mathbf{CM^T} \tag{6}$$

2.2 Normalization

The duration time of the standing-up motion is different among different trials and different subjects. In order to compare different trials, the duration time needs to be normalized.

To normalize the duration time, the standing-up motion is divided into four phases. The start time of phase 1 is set as the start of standing-up motion. The end time of phase 4 is set as the end of the motion. The start time of phase 1 is when the horizontal velocity of shoulder exceeds 0.2 m/s. The start time of phase 2 is when the vertical reaction force of hip is less than 0 N. The start time of phase 3 is when the horizontal displacement of the knee gets its maximum. The start time of phase 4 is when the vertical velocity of shoulder becomes less than 0.1 m/s after the start time of phase 3. The end time of phase 4 equals to the start time of phase 4 adds the 25% of the duration time from phase 1 to phase 3.

Because the stabilization strategy takes more time than momentum transfer strategy, we normalize the duration of each standing-up motion to 100

3 Experiment

3.1 Experiment Conditions

In this experiment, four healthy male subjects (25.3±2.8 years old) were asked to do standing-up motion using two strategies (momentum transfer and stabilization). For each strategy, there were 15 trials. Duration time of each trial was 10 s. The chair height was adjusted to the height of lower leg. The ankle joint angle of the subject was fixed to 80 degrees from the horizontal direction at the initial state of the experiment.

3.2 Experimental Setup

In this experiment, motion capture system (Motion Analysis. Corp.) was used to get the kinematics information of the subject in 100 Hz. This motion capture system has eight infrared cameras. There were 20 markers put according to Helen Hayes marker set to reflect the infrared ray. In this way, the motion capture system could obtain joint position data. Joint angle data was calculated using SIMM (Musculographis Inc.) based on the joint position data.

Surface EMG device (DL-141, S&ME Corp.) was used in this experiment to get muscle activities data in 1000 Hz. Ten muscles related to standing up motion were measured according to their contribution to extend or flex the ankle, knee, and hip joints [12]. The 10 muscles name and position are shown in Table 1. Two force plate devices (TechGihan. Corp.) were used to get the reaction force data in 1000 Hz. Experiment environment is shown in Fig. 2.

3.3 Results

Figures 3 and 4 show the coefficient of determination of momentum transfer and stabilization strategies of different numbers of muscle synergies.The results showed that four muscle synergies could represent more than 90% muscle activations of the two strategies. Therefore, four synergies are used in this

Table 1: Measured muscles in the experiment

Muscle Name	Contribution to Joints
1. Tibialis Anterior (TA)	Dorsi-flexes ankle
2. Gastrocnemius (GAS)	Planter-flexes ankle and flexes knee
3. Soleus (SOL)	Planter-flexes ankle
4. Rectus Femoris (RF)	Flexes knee
5. Vastus Lateralis (VAS)	Extends knee
6. Biceps Femoris Long Head (BFL)	Flexes knee and extends hip
7. Biceps Femoris Short Head (BFS)	Flexes knee
8. Gluteus Maximus (GMA)	Extends hip
9. Rectus Abdominis (RA)	Flexes lumbar
10. Elector Spine (ES)	Extends lumbar

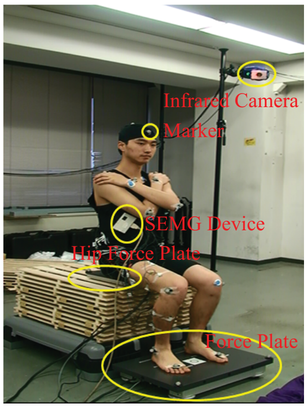


Fig. 2: Experiment Environment

research. Figures 5 (a), (c), (e) and (g) show the spatial patterns of four muscle synergies which are used to explain muscle activation of the 10 selected muscles. Black and white bars show relative muscle activation when subjects used momentum transfer and stabilization strategies respectively. Each synergy had particular contribution to body movements according

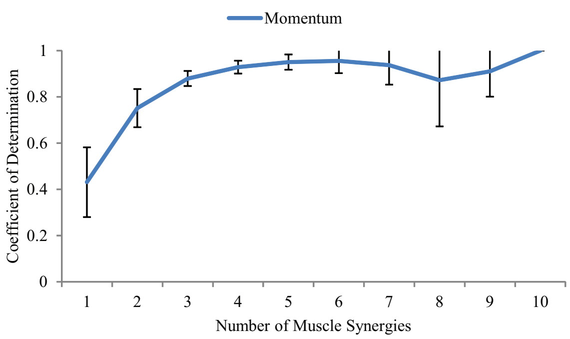


Fig. 3: Coefficient of determination (Momentum transfer strategy)

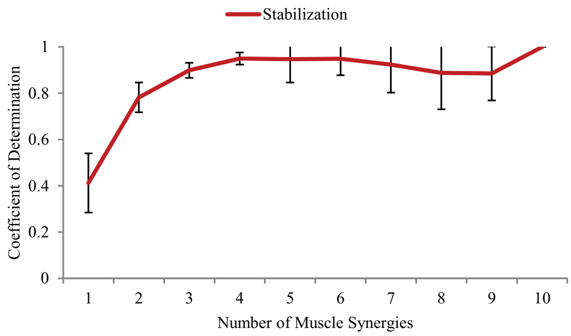


Fig. 4: Coefficient of determination (Stabilization strategy)

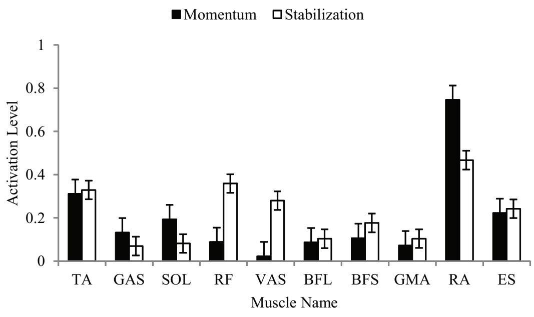
to human anatomy. In Fig. 5 (e), it shows that muscle synergy 1 mostly activated RA which flexed the lumbar and produced momentum for the standing-up motion. Muscle synergy 2 mostly activated TA which dorsiflexed ankle joint to move CoM forward, and activated VAS and RF to extend knee, as Fig. 5 (c) shows. In Fig. 5 (e), muscle synergy 3 mainly activated ES and VAS to extend trunk and knee, which extend the whole body and move the CoM upward. Figure 5 (g) shows that muscle synergy 4 activated GAS and SOL, which flexes knee and ankle to decelerate movement of CoM.

Figures 5 (b), (d), (f) and (h) show the temporal patterns of the four muscle synergies. The weighting coefficients of temporal patterns are on the vertical axis. The duration time of the whole standing-up motion is on the horizontal axis, and the time was normalized to 100%. The black solid lines and black dashed lines show the temporal patterns of momentum transfer and stabilization strategies. In Fig. 5 (b), muscle synergy 1 was activated to flex the lumbar and start the bending forward motion, and it ended at 60% time of the whole motion. Figure 5 (d) shows that synergy 2 started to activate muscles at 10% time of the whole motion. Figure 5 (f) shows that synergy 3 started to activate muscle at 20% time of the whole motion. Figure 5 (h) shows that it started at 40% and activates GAS and SOL to plantarflex ankle and extend knee joint.. Muscle synergy 4 is important for humans to decelerate their horizontal CoM movement and keep balance. For all the temporal patterns shown in Fig. 5, the start time are earlier in the case of momentum transfer strategy.

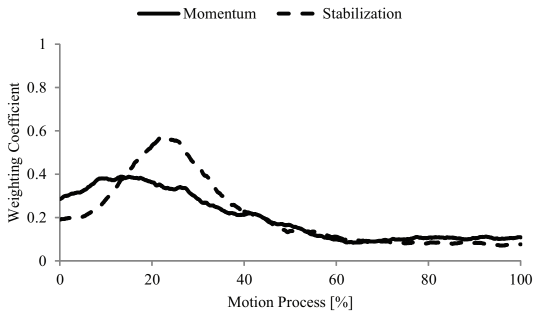
4 Discussion

In this study, the muscle synergy model was used to clarify differences in various strategies in human standing-up motion. The experiment result showed that four muscle synergies could successfully represent standing-up motion.

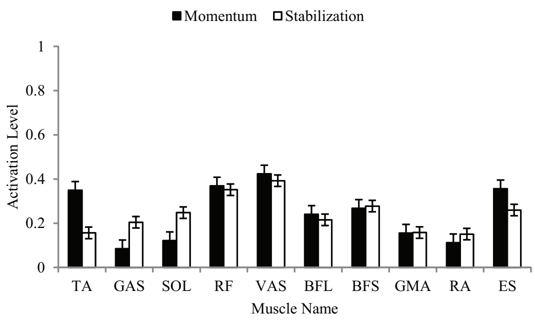
From spatial patterns shown in Fig. 5, the two strategies mainly activate the same muscles. The spatial patterns 2, 3, and 4 are similar. However, there are still some differences. In spatial pattern of mus-



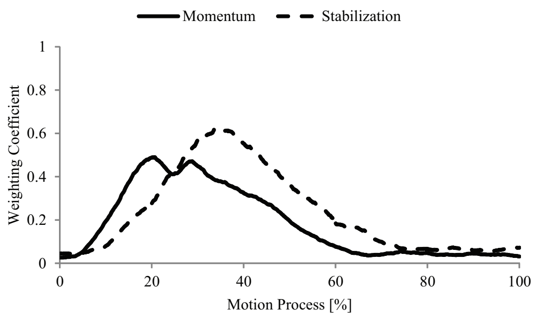
(a) Spatial pattern of muscle synergy 1



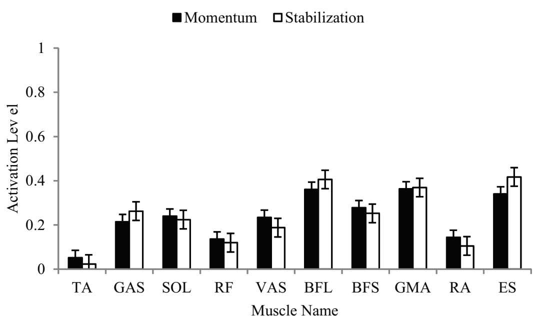
(b) Temporal pattern of muscle synergy 1



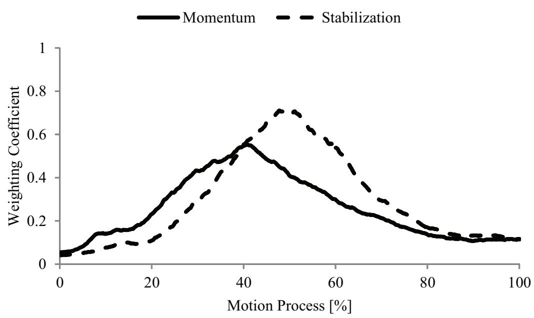
(c) Spatial pattern of muscle synergy 2



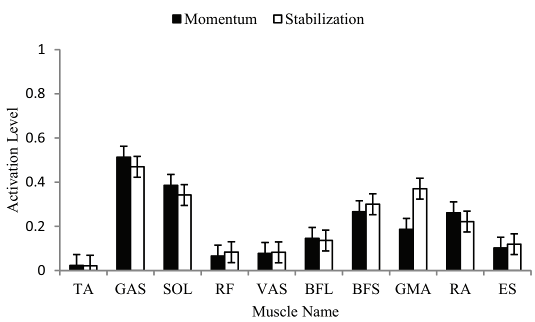
(d) Temporal pattern of muscle synergy 2



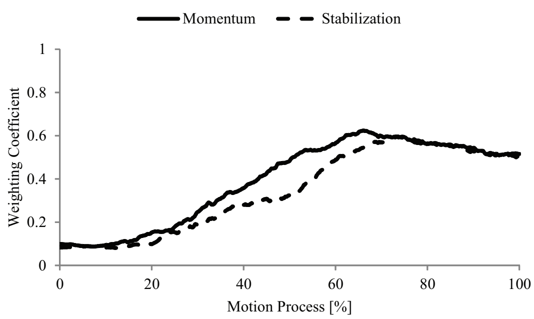
(e) Spatial pattern of muscle synergy 3



(f) Temporal pattern of muscle synergy 3



(g) Spatial pattern of muscle synergy 4



(h) Temporal pattern of muscle synergy 41

Fig. 5: Spatial and temporal pattern of four muscle synergies.

cle synergy 1, the activation level of RF and VAS are higher when the subject used stabilization strategy. When using stabilization strategy, the subject planned to keep balance rather than move fast. It takes longer time to flex the joint and to generate the momentum. On the other hand, the activation level of RA is higher when the subject used momentum transfer strategy. This is because when using momentum transfer strategy, the subject tried to move upward directly. RA was activated to generate momentum.

Although the spatial patterns are similar, temporal patterns are different. The start time was earlier in the case of momentum transfer strategy. In addition, the amplitude of muscle synergy 3 of stabilization strategy was larger than that of momentum transfer strategy. When the muscle synergy started ealier, the subject began to move upward ealier before its horizontal CoM move forward. On the other hand, when the muscle synergy started later, the subject move upward after the horizontal CoM move forward. The differeces between the two strategies in start time is also associated with the results of peak time and CoM. Previous simulation study also reported the same phenomenon that the start time of momentum is earlier than stabilization [4]. The literature found that standing-up motion strategies could be generated by controlling the start time of muscle synergy 3. In stabilization strategy, humans move more slowly. That means they have less momentum since momentum is generated from mass and velocity. These parameters can be used to distinguish the two strategies and evaluate how humans generate different strategies. In this way, we can find that how differenct strategies contribute to function and stability.

5 Conclusion

In this study, muscle synergy model was developed to analyze how humans utilized muscle synergy to generate standing-up motion. Experiment result verified that four muscle synergies could successfully represent human standing-up motion. Moreover, the experimental result showed that two strategies (momentum transfer and stabilization) in standing-up motion could be distinguished by comparing the start time, peak time and amplitude of temporal patterns. For future work, the differences of temporal patterns will be compared between the trajectories of CoM.

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