Clarification of Muscle Synergy Structure During Standing-up Motion of Healthy Young, Elderly and Post-Stroke Patients*

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概要 Standing-up motion is an important daily activity. It has been known that elderly and post-stroke patients have difficulty in performing standing-up motion. The standing-up motion is retrained by therapists to maximize independence of the elderly and post-stroke patients, but it is not clear how the elderly and post-stroke patients control their redundant muscles to achieve standing-up motion. This study employed the concept of muscle synergy to analyze how healthy young adults, healthy elderly people and post-stroke patients control their muscles. Experimental result verified that four muscle synergies can represent human standing-up motion. In addition, it indicated that the post-stroke patients shift the activation time of muscle synergies to finish standing-up motion comparing to healthy subjects. Moreover, different muscle synergy structures were associated with the trajectories of CoM.

キーワード: standing-up motion, muscle synergy, stroke patients

1 Introduction

Nowadays, many people suffer from motor impairment, such as the elderly and stroke patients. According to 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 is estimated that it will increase more rapidly to reach 21% in 2050 [1]. The number of stroke patients increased by 800,000 each year [2]. In order to improve the quality of life of the elderly and stroke patients, the standing-up motion is focused as one of the most common daily activities, which usually followed by other activities. For the elderly and post-stroke patients with lower extremity muscle weakness, it is difficult to rise from a chair because of muscle weakness. Hence, the standing-up motion is retrained by therapists to maximize independence of the elderly and post-stroke patients.

To retrain the elderly and the post-stroke patients efficiently, it is important to understand the mechanism of the standing-up motion. Hughes et al. defined three strategies (momentum tansfer, stabilization, and hybrid) used in humans standing-up motion which generate different movements [3]. They found that younger persons tend to use the momentum transfer strategy which utilizes the momentum to lift up their body. On the other hand, the elderly persons tend to use the stabilization strategy in which they carry their center of mass (CoM) first on their feet and then they move upward. Other studies also found that post-stroke patients have delayed muscle activation compared to healthy elderly people [4]. In order to clarify how humans coordinate their redundant number of muscles to generate different standing-up movements, the concept of muscle synergy has been employed in the area of human motor control theory. Muscle synergy was firstly proposed by Bernstein, which suggested that human movements could be generated from a limited number of modules (called muscle synergy) [5]. Our previous studies employed both forward dynamic simulation and measurement experiment to clarify the muscle synergy structure of different standing-up strategies [6]. However, these studies were based on healthy young adults. It is still unclear how the healthy elderly people and post-stroke patients coordinate redundant muscles to achieve standing-up motion. Therefore, we perform the standing-up motion experiment of healthy elderly people and post-stroke patients in this study. We aim at clarifying the muscle synergy structure in standing-up motion of the healthy elderly people and post-stroke patients.

2 Method

For the muscle synergy model, muscle activation can be expressed as a linear summation of spatiotemporal patterns in a mathematical expression, as in Eq. (1),

$$\mathbf{M} = \mathbf{W}\mathbf{C}, \qquad (1)$$

where matrices $\mathbf{M}$, $\mathbf{W}$, and $\mathbf{C}$ indicate muscle activation, spatial pattern and temporal pattern matrices respectively. Spatial pattern $\mathbf{W}$ is used to represent the relative activation level of muscle, and temporal pattern $\mathbf{C}$ is used to indicate the weighting coefficient of muscle synergy. To calculate elements of matrices $\mathbf{W}$ and $\mathbf{C}$, non-negative matrix factorization algorithm is used [7]. Muscle activation matrix is obtained from measurement experiment described in the next section.

*本研究は 15th IEEE International Conference on Rehabilitation Robotics で発表したものである．

3 Experiment

3.1 Experimental Setting

In this experiment, six healthy young adults (25±3.0 years old), five healthy elderly participants (66.8±8.5 years old) and three post-stroke patients (58.3±11.4 years old) were asked to stand up from their own comfortable feet location. All of the subjects could stand up from a chair by themselves without any support. A motion capture system (Motion Analysis) with eight infrared cameras was used to get kinematics data of the subject. Surface EMG device (DL-141, S&ME) was used to measure muscle activities. Fifteen muscles which contribute most in standing-up motion were measured and spatial pattern of muscle synergy is different from muscle activation level. Two force plates (TF-4060, TechGihan) were used to obtain the reaction force data.

3.2 Results

For the center of mass (CoM) movements, the result shows that healthy young adults and the elderly moved the CoM upward before the CoM reaching the feet position. Therefore, the young and the elderly needed to decelerate the horizontal CoM movement to keep balance at the end of the motion. This is related to the results of temporal pattern of muscle synergy 4. The healthy young adults and the elderly reached the peak time ealier than that of the post-stroke patients. Comparing to the healthy young adults and the elderly, the post-stroke patients firstly moved the CoM to the feet to make the standing-up motion more stable.

For the healthy young adults and the elderly, the coefficients of determination R^2 were 94±2% and 88±3% when the number of muscle synergies was four. This indicate that four muscle synergies can represent most of the muscle activation during the standing-up motion. Similarly, R^2 was 88±4% for the post-stroke patients and when four muscle synergies were used to represent muscle activation. In addition, more numbers of muscle synergies increased the value of R^2 little.

The results showed that spatial patterns of two strategies were similar. For muscle synergy 1, rectus abdominis was mostly activated to generate momentum for motion. Muscle synergy 2 mainly activated tibialis anterior, which contributed to dorsiflex ankle joint to move forward. Muscle synergy 3 activated erector spine to extend the body and move upward. Muscle synergy 4 mainly activated gastrocnemius and soleus to decelerate movement. This implies that spatial patterns of muscle synergies would be preserved even in the post-stroke patients as well.

However, parameters of temporal patterns such as duration time and peak time were different. Muscle synergy 1 was firstly activated and it shows that the post-stroke patients had longer time to bend their trunk forward. This difference results in the downward movement of CoM at the beginning of their movement whereas downward movement was not observed for the young and the elderly. The characteristic difference was observed in the temporal patterns of muscle synergy 2. It shows that the peak times come in the order of the young, the elderly, and the stroke patients. Duration time of phase 2 is also the longest in the patients (28%) compared to the young (13%) and the elderly (17%). Similarly the gradient after the peak value differs in three types of the subjects. The patients had the least steep gradient, the elderly had the second steepest gentle one, and the young had the steepest gradient. Taking CoM trajectory into account, this phenomena is related to the horizontal CoM movement. This implies that humans control the activation timing and duration of the muscle synergy 2 to control horizontal CoM movement. In muscle synergy 3, temporal patterns of the post-stroke patients differed from the young and the elderly. Since the start time is the latest in the post-stroke patients, the peak time was delayed accordingly. As it has been discussed above, the patients firstly move the CoM on the feet and then start moving upward. Delayed activation of the muscle synergy 3 resulted in the late upward movement. At last, the muscle synergy 4 was activated to decelerate the horizontal movement. As well as other synergies, the gradient became more gentle in the order of the post-stroke patients, the elderly, and the young. This phenomena could be interpreted as the compensation of the forward horizontal movement of the muscle synergy 2. When the muscle synergy 2 activated latter and its gradient became gentle, the same trend was observed for the muscle synergy 4 accordingly. This compensated activation is considered to be important because this maintains the CoM on their feet. If the post stroke patients cannot control the start time of the muscle synergy 4 properly, the movement would result in falling down.

4 Conclusion

In this study, muscle synergy model was employed to analyze how the healthy young adults, the healthy elderly people and post-stroke patients controlled their muscles to do standing-up motion. Experimental result verified that four muscle synergies could represent human standing-up motion. Our findings showed that the spatial pattern of the muscle synergies were common among the young, the elderly and patients. However, the post-stroke patients could use the same muscle synergies to achieve a more stable strategy of standing-up motion in which they firstly move their CoM on their feet and extend their body upward. The results showed the possibility that the humans changed temporal patterns of muscle synergy to realize the different standing-up motion strategies.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number 26120005 and 16H04293.

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