Temporal Structure of Muscle Synergy of Human Stepping Leg During Sit-to-Walk Motion

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Abstract. In daily lives, humans successfully transit their motions rather than performing separate movements. It has been widely acknowledged that there are four and five modules (called muscle synergy) in human sit-to-stand and walking motions, but it was still unclear how humans activate their redundant muscles to transit their movement from sitting to walking. Therefore this study hypothesize that human sit-to-stand can be explained from muscle synergies of sit-to-stand and walking motions, and we perform the experiment to verify it. Firstly, four and five muscle synergies were obtained from sit-to-stand and walking motion, and it has been tested whether these nine synergies are applicable to sit-to-walk motion. Results showed that sit-to-walk motion were successfully explained from nine synergies. Moreover, it was shown that humans adaptively changed the activation time of each synergies to delay body extension time and to generate necessary initial momentum for the walking motion.

Keywords: sit-to-walk, muscle synergy, motion analysis

1 Introduction

Aging society has become a serious issue these days, and many elderly people have been suffering from declined physical ability. This situation increases the social security cost and it also becomes a big burden to care givers. In order to solve these problems, it is important to firstly evaluate human body function and to develop a training methodology for the impaired mobility. However, it has not been clear how humans achieve their movement. Particularly it has been widely acknowledged that human body is a redundant system that the number of the muscles is much larger than that of the joints. To develop the efficient training protocol, it is necessary to know how humans control this redundant degrees of freedom.

To this end, our research group has employed the idea of muscle synergies. The muscle synergy was firstly proposed by Bernstein which stated that human body was controlled by the small number of modules (called synergies) rather than activating individual muscles [1]. In our previous study, we have been focusing on human sit-to-stand (STS) motion and we found that four muscle synergies could explain the motion [2]. Similarly it was suggested that human locomotion could be accounted mainly by five modules [3]. Another study investigated the muscle activation of the spinal cord injury patients and they found that muscle synergy structure was quiet different from the healthy ones [4]. These previous findings implied that humans could utilize muscle synergies to achieve the motion and the movement would be disturbed with the impaired synergies. These findings also suggest the possibility which muscle synergies as an evaluation markers for the impaired function.

These studies, including our research, did investigate STS and walk motions in different conditions. Although these findings are limited to the single motion, humans usually have to combine the several motions or to transit one motion to another in daily lives rather than performing a individual movement. In particular, humans do not only stand up from a chair, but this movement will lead to the locomotion. Although previous studies suggested that four and five muscle synergies could been used for human STS and walking motions, it is unclear whether humans utilize the same module to transit their movements.

In fact, many medical and rehabilitation hospitals use this sit-to-walk (STW) motion in Timed Up and Go (TUG) test to evaluate body function of the elderly [5]. The test measures the time from when people stand up from a chair until they come back and sit down on the chair again after 6 m walk. Although this test only measured the time to perform the motions, it was known that the taken time is strongly co-related to the dynamic stability of the elderly. If we could clarify the necessary muscle activation structure in STW motion, it would provide more evidence for the TUG test.

There are a few studies which analyzed STW movements. One previous study analyzed body trajectory and reaction force during STW and they found that the young persons could transit the motions more smoothly than the elderly by generating more initial momentum [6]. Another research group defined four characteristic event also based on kinematics and reaction force [7][8]. Other researchers investigated muscle activity, kinematics and reaction force to find activation order of each muscle and also revealed the relationship between the knee torque and hip flexion [9]. It has been also emphasized that there were merging of two tasks in STW motion rather than performing separate tasks [10]. These previous studies showed that STW was not achieved only by serial arrangement of two tasks but there was a fusion of two tasks. However, they mainly considered kinematic movement or center of pressure and they have not yet clarified how they controlled redundant muscles.

Therefore, this study analyzes human STW in terms of their muscle activity. In particular we hypothesize that modular organization (muscle synergy) of STS and walking can account for STW movement. Moreover, it will be investigated how these modules are adaptively coordinated in order to achieve STW motion.

2 Methods

2.1 Muscle Synergy Model

This study analyzes human motion based on the muscle synergy model. Firstly muscle synergy model is explained in detail. Muscle synergy model assumes that various human movements can be explained by the limited number of the modules. Particularly it supposes that these module are composed of synchronized muscle activation and humans control their weight to properly achieve different motion. In a mathematical expression, it is often expressed that muscle activation could be generated from linear summation of spatiotemporal patterns as in following equations,

$$\mathbf{M} = \mathbf{W}\mathbf{C}, \tag{1}$$

where matrix $\mathbf{M} \in \mathbb{R}^{n \times t_{\max}}$ indicates muscle activation. Each row of the matrix $\mathbf{m}_{i=1\cdots n}$ represents time series of n different muscle activation (eq. (2)). The matrix $\mathbf{W} \in \mathbb{R}^{n \times k}$ shows spatial patterns which indicates relative activation level of each muscle, and each column of the matrix $\mathbf{w}_{i=1\cdots k}$ represents separate modules (eq. (3)). The matrix $\mathbf{C} \in \mathbb{R}^{k \times t_{\max}}$ represents temporal patterns which is time-varying weighting coefficient of the muscle synergies, and the row of the matrix $\mathbf{c}_{i=1\cdots k}$ shows different temporal patterns (eq. (4)).

$$\mathbf{M} = \begin{pmatrix} \mathbf{m}_1(t) \\ \mathbf{m}_2(t) \\ \vdots \\ \mathbf{m}_n(t) \end{pmatrix} = \begin{pmatrix} m_1(1) & \cdots & m_1(t_{\max}) \\ \vdots & \ddots & \vdots \\ m_n(1) & \cdots & m_n(t_{\max}) \end{pmatrix}, \tag{2}$$

$$\mathbf{W} = (\mathbf{w}_1 \cdots \mathbf{w}_N) = \begin{pmatrix} w_{11} & \cdots & w_{1k} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nk} \end{pmatrix}, \tag{3}$$

$$\mathbf{C} = \begin{pmatrix} \mathbf{c}_1(t) \\ \mathbf{c}_2(t) \\ \vdots \\ \mathbf{c}_N(t) \end{pmatrix} = \begin{pmatrix} c_1(1) & \cdots & c_1(t_{\max}) \\ \vdots & \ddots & \vdots \\ c_k(1) & \cdots & c_k(t_{\max}) \end{pmatrix}. \tag{4}$$

Figure 1 shows the concept of the muscle synergy model; vertical bars in each square indicate spatial patterns (the left side of Fig. 1(a)), the solid line, the dashed line, the line with circles represent temporal patterns corresponded to each spatial pattern (the middle side of Fig. 1(b)), and linear summation of these spatiotemporal patterns generates muscle activation (the right side of Fig. 1(c)). In order to calculate spatiotemporal patterns $\mathbf{W}$ and $\mathbf{C}$ of muscle synergies, non-negative matrix factorization (NNMF) [11] needs to be applied to muscle activation data $\mathbf{M}$. When using NNMF, the number of muscle synergies need to be determined beforehand, and it is decided as four for STS motion [2] and as five for walking motion [3] based on previous research. In this study, muscle activation ($\mathbf{M}^{\mathrm{STS,Walk,STW}}$) during each condition is obtained in the measurement experiment.

In order to validate our hypothesis that muscle activity during STW could be explained from muscle synergies of STS and walking, we firstly extract spatiotemporal patterns ($\mathbf{W}^{\mathrm{STS}}$, $\mathbf{C}^{\mathrm{STS}}$, $\mathbf{W}^{\mathrm{Walk}}$ and $\mathbf{C}^{\mathrm{Walk}}$) of muscle synergies from STS and walking motions respectively. Next, we use the extracted spatial patterns ($\mathbf{W}^{\mathrm{STS}}$ and $\mathbf{W}^{\mathrm{Walk}}$) to investigate whether these patterns could explain muscle activation during STW motion well enough. This could be achieved by the optimization methodology [12] to find the optimal temporal patterns $\mathbf{C}^{\mathrm{STW}}$ to minimize following squared error z,

$$z = |\mathbf{M}^{\mathrm{STW}} - \mathbf{W}^{\mathrm{STS,Walk}}\mathbf{C}^{\mathrm{STW}}| \quad \text{when given } \mathbf{M}^{\mathrm{STW}} \text{and } \mathbf{W}^{\mathrm{STW}}, \tag{5}$$

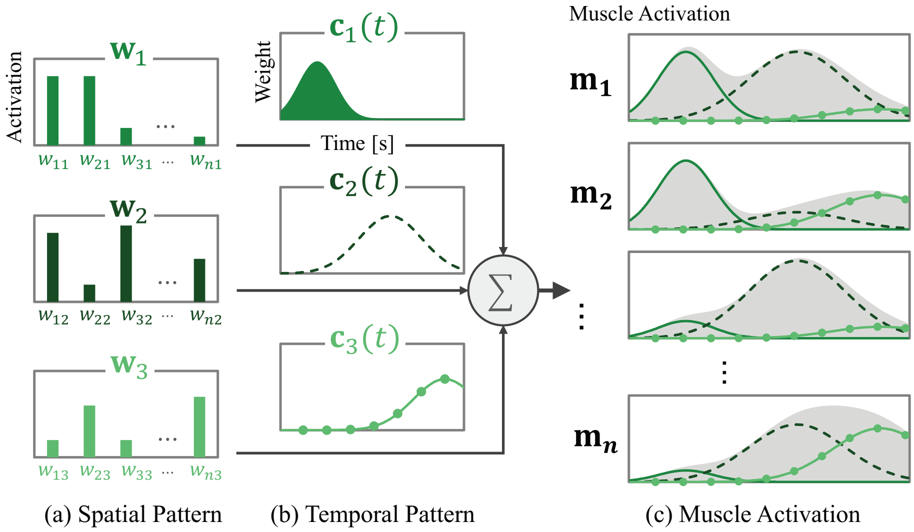


Fig. 1. Muscle Synergy Model. (a) shows spatial patterns ($\mathbf{w}_{1,2,3}$) which indicates relative excitation level of each muscle. (b) shows temporal patterns ($\mathbf{c}_{1,2,3}$) to define time-varying weighting coefficient of corresponded muscle synergies. (c) shows time-varying activation for n muscles (gray part). Red, blue, and green dashed lines show generated activation from muscle synergies 1, 2, and 3 respectively.

where $\mathbf{M}^{\mathrm{STW}}$ is muscle activation during STW motion and $\mathbf{W}^{\mathrm{STW}}$ is composed of $\mathbf{W}^{\mathrm{STS}}$ and $\mathbf{W}^{\mathrm{Walk}}$. To evaluate how well the spatial patterns during STS and walking explain muscle activation of STW, coefficient of determination R^2 is calculated.

The most moved joints during STS, walking and STW are ankle, knee, hip and lumbar. Therefore, this study particularly investigates major ten muscles which could account for both flexion and extension movement of these joints. Considered muscles are as follows; tibialis anterior (TA), gastrocnemius (GAS), soleus (SOL), rectus femoris (RF), vastus lateralis (VAS), biceps femoris long head (BFL), biceps femoris short head (BFS), gluteus maximus (GMAS), rectus abdominis (RA), erector spine (ES). All the muscles are shown in Fig. 2.

2.2 Experiment

Measurement experiment was conducted to record body trajectory, reaction force and muscle activity during STS, normal walking and STW motions. Figure 3 shows our experimental setup.

Experimental Setup Eight motion capture cameras (Raptor-H; Motion Analysis Corp.) were used to measure the body trajectory in 100 Hz. Reflective markers were attached to the participant body based on the Helen Hayes marker set. Reaction force from feet

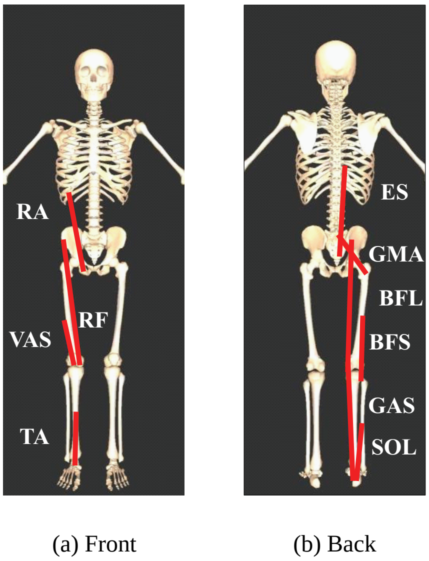


Fig. 2. Considered Muscles. (a) and (b) respectively show measured muscles from front and back views. Ten muscles are considered which either flex or extend ankle, knee, hip and lumbar joints.

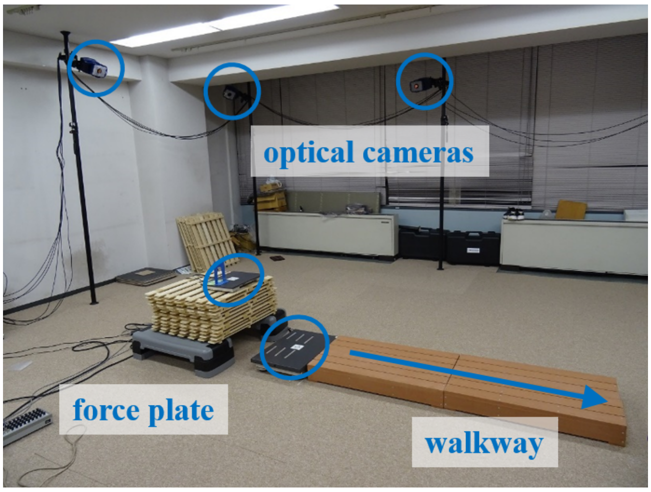


Fig. 3. Experimental Setup. Eight optical cameras were used to measure the body trajectory and two force plates were placed below the feet and hip to record reaction force. Wood blocks were put in front of the force plate to ensure that participants could perform STW motion continuously.

and hip was measured in 1,000 Hz by two forceplates (TF-4060 and TF-3040; TechGihan Co., Ltd.). Figure 3 shows our experimental setup. Muscle activation was measured in 1,000 Hz from surface electromyography sensor (DL-141 and DL-721; S&ME, Inc.). EMG sensors were attached to the right leg of the participants. In order to standardize the muscle activity among different trials and participants, it was normalized to 0–1 based on the maximum and minimum values in every trial. All the recorded data was filtered; body position data was filtered with the second order butter worth low pass filter with 5 Hz, reaction force data was low pass filtered with 20 Hz, and muscle activation data was filtered with the band pass filter of 60–200 Hz. Recording time for each trial was 10 s.

Experimental Condition Three young male (23.7 $\pm$ 0.6 years) participated at our experiment. Firstly, participants were asked to stand up from the seated position in the comfortable speed. The chair height was adjusted to the knee height of each subject. Also they were told to cross their arms in front of their chest in order to avoid usage of the arms. Next, subjects were asked to perform STW motion. They were instructed to stand up and to transit continuously to the walking motion. The participants were asked to perform locomotion on the 1.8 m walkway as shown in Fig. 3. All of them was told to take the initial step from the right leg, and they stop walking until they took three steps. At last, participants were asked to perform walking motion from the standing posture. In this case, the subjects also started their motion from the right side and performed three steps. Fifteen trials were obtained from every condition.

Figure 4 shows kinematic movements during STW motion. The participants firstly rise their hip and they initiate the first step from the right leg. Some characteristic events are depicted in the vertical lines such as hip rise, toe lift and heel strike. White and gray squares between vertical lines show whether the leg is in swing or stance phases. These events could be obtained from measured kinematic and force data. The time of hip rise was determined when the vertical reaction force of the hip became less than 5.0 N. The toe lift timing was decided when the vertical velocity of the toe became positive. The heel strike time was decided when the vertical velocity of the heel became lager than -0.015 m/s after its deceleration.

Duration of all the trials were normalized in order to compare different conditions. Movement time of STS was decided based on characteristic kinematic movement. The start time of STS was when the participants started to bend their trunk. The end time for the motion could not be determined clearly since humans only stand straight after their standing-up. Therefore, we firstly calculate the time between the start time and the time when the participants reached the highest shoulder position. Next, the end time of STS was decided as it was 125% of the period between the first bending and the straight standing. Duration time of walking condition was decided to the period from the first heel strike to the next heel strike. In the experiment, one cycle of walking motion was used from each trial.

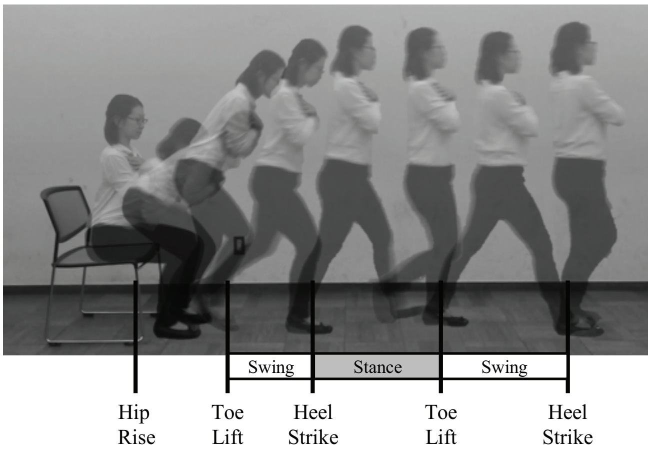


Fig. 4. Kinematic Event during STW Motion. Above figure shows STW movement and the vertical lines show characteristic event such as hip rise, toe lift, heel strike. Squares show duration of swing and stance phase during walking.

3 Results

From measured muscle activation, four and five muscle synergies were extracted for STS and walking motions respectively. Using these extracted nine modules ($\mathbf{w}_{1\cdots4}^{\mathrm{STS}}$ and $\mathbf{w}_{1\cdots5}^{\mathrm{Walk}}$), the temporal patterns were obtained through the optimization methodology. The coefficient of determination R^2 was 0.88±0.02 when muscle activation of STW was explained by modules of STS and walking.

Figure 5 shows spatiotemporal patterns during STS and STW motions. The left graphs (Fig. 5(a)) show mean and standard deviation of the spatial patterns during STS movement. In the middle (Fig. 5(b)), these stick pictures indicate corresponded movement. The arrows indicate the directions of the joints to be moved. The right graphs in Fig. 5(c) show the temporal patterns compared between STW and STS motions. Temporal patterns of STS are shown in colored filled area and ones of STW are shown in solid lines. The vertical lines represent the time of hip rise and squares on the horizontal axis represent duration of swing and stance phases. Mainly activated muscles in each spatial patterns had the same characteristics as the ones reported in the previous study [2]. The first module ($\mathbf{w}_1^{\mathrm{STS}}$) in STS motion activated RA to bend their trunk forward. The second module ($\mathbf{w}_2^{\mathrm{STS}}$) activated TA, VAS and RF to dorsiflex the ankle and extend the knee to rise from the chair. The third module ($\mathbf{w}_3^{\mathrm{STS}}$) activated VAS, RF, BFL, BFS and ES to extend the knee and the lumbar joints. The last module ($\mathbf{w}_4^{\mathrm{STS}}$) activated SOL and GAS to plantarflex the ankle joint to stabilize their posture.

Similarly, Fig. 6 shows the spatial patterns in walking and STW motions (Fig. 6(a)), corresponded kinematics (Fig. 6(b)), and temporal patterns during walking and STW motions (Fig. 6(c)). Spatial patterns in walking motion also have the similar characteristics The first module ($\mathbf{w}_1^{\mathrm{Walk}}$) activated TA to plantarflex the ankle to control the feet during the swing phase. The second module ($\mathbf{w}_2^{\mathrm{Walk}}$) activated BFL and BFS to pull the knee to avoid their shank to hit the ground. The third module ($\mathbf{w}_3^{\mathrm{Walk}}$) activated VAS, RF and GMA to extend the knee and the hip to absorb impact force of heel strike. The fourth module ($\mathbf{w}_4^{\mathrm{Walk}}$) activated SOL and GAS to dorsiflex the ankle to move the body forward. The last module ($\mathbf{w}_5^{\mathrm{Walk}}$) activated ES to extend the lumber to control upper body.

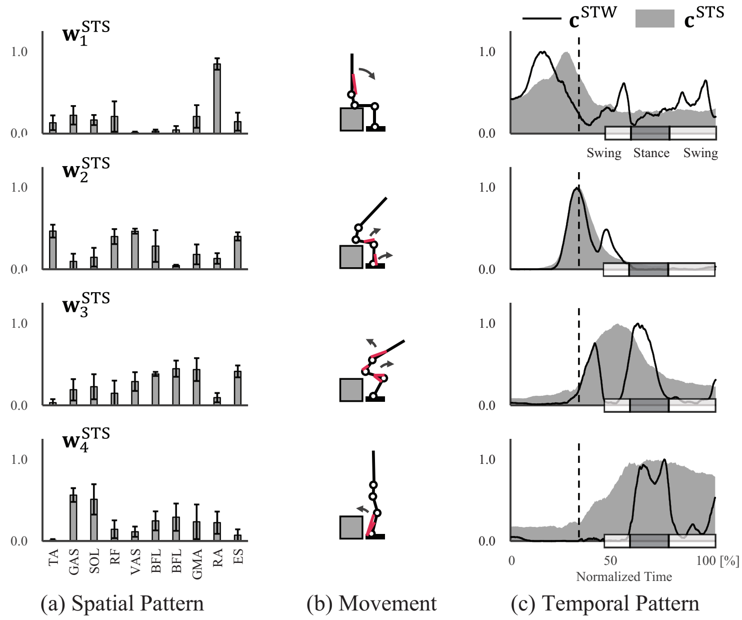
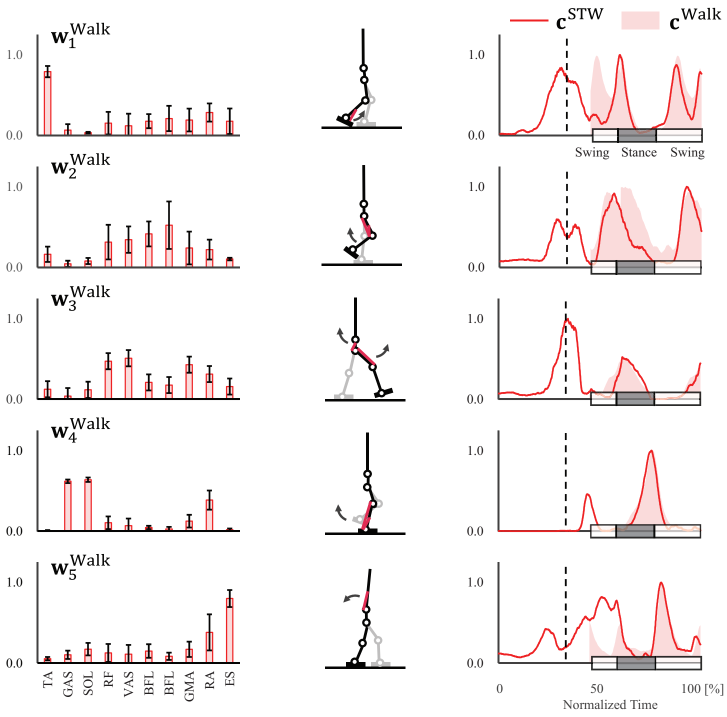


Fig. 5. Muscle Synergy Results in STS and STW motion. (a) Spatial patterns of extracted synergies are shown above. Four synergies are obtained from STS motion. (b) These stick pictures show corresponded movements to each spatial pattern. Red lines represent mainly activated muscle. (c) Above graphs show the temporal pattern of STW (solid lines) and STS motions (colored area).

4 Discussion

Our results showed that muscle synergies of STS and walking motions could explain the most part of the muscle activation during STW motion (88%). This implied that humans did not need additional modules while they transited the motion from standing-up to walking. Although the same modules were applicable to the STW motion, their activation profiles (temporal patterns) were different from their initial motions (STS and walking).



(a) Spatial Pattern (b) Movement (c) Temporal Pattern

Fig. 6. Muscle Synergy Results in Walking and STW motion. (a) Spatial patterns of extracted synergies are shown above. Five synergies are obtained from walking motion. (b) These stick pictures show corresponded movements to each spatial pattern. Red lines represent mainly activated muscle. (c) Above graphs show the temporal pattern of STW (solid lines) and walking motions (colored area).

The temporal pattern of the first module of STS ($\mathbf{w}_1^{\mathrm{STS}}$) did not differ a lot for STW ($\mathbf{c}_1^{\mathrm{STW}}$) from the initial temporal pattern of STS ($\mathbf{c}_1^{\mathrm{STS}}$). On the contrary, other three modules of STS had significant difference compared to the temporal patterns of STS. Temporal pattern of the second module for STW ($\mathbf{w}_2^{\mathrm{STS}}$) had one additional peak compared to the one of STS ($\mathbf{c}_2^{\mathrm{STS}}$). Focusing on the second peak, it was activated at the time of toe lift, and this implied that the second module was also utilized for the different movement (lifting up their toe). The third module ($\mathbf{w}_3^{\mathrm{STS}}$) had a similar activation profile until the participants lifted up their toe. However, the activation disappeared during the early swing phase but it would be re-activated toward the stance phase. Considering the original contribution of the third module (body extension), this phenomenon implied that humans did not fully extend their upper body, but they instead did so during the stance phase. Similarly, the forth module ($\mathbf{w}_4^{\mathrm{STS}}$) did not activate at all in STW at the time when it used to be activated in STS. Since, the last module contributed to posture stabilization by plantarflex the ankle joint, humans did not need this movement when they transit the motion from standing-up to walking. Instead, it was activated at the stance phase after the participants started walking. These results indicated that the same modules of STS could be utilized for STW motion, but one of the modules ($\mathbf{w}_2^{\mathrm{STS}}$) were activated in different ways to serve alternative movement of lifting up toes or some of them ($\mathbf{w}_3^{\mathrm{STS}}$ and $\mathbf{w}_4^{\mathrm{STS}}$) had the shifted activation peak.

The modules of walking were also utilized differently in STW motion. One of the findings was that in STW humans activated their modules very similarly to the one in walking motion from the time of the first heel strike. From Fig. 6(c), it could be found that temporal patterns of STW ($\mathbf{C}_{1\cdots5}^{\mathrm{STW}}$) had very similar peak as the ones of walking ($\mathbf{w}_{1\cdots5}^{\mathrm{Walk}}$). Since walking motion required phasic activation of each module [3], this indicated that the participants initialized the walking program from the first step even in STW motion. Moreover three modules ($\mathbf{w}_{1,2,3}^{\mathrm{Walk}}$) needed to be activated before starting lifting up the toe. In particular, they had a peak at the time of hip rise. This phenomenon implied that humans needed additional activation to activate TA, BFL, RF, VAS and GMA to generate more momentum to transit the motions.

Based on the above findings, it could also be implied that humans could utilize both modular organization of STS and walking at the same time. This results corresponded to the previous study [10] to suggest that there was merging of two task in transition phase. Moreover our study could reveal how humans utilized their individual modules of STS and walking motions in STW.

5 Conclusion

This study hypothesized that human transit the motion from sitting to walking could be accounted by the same muscle synergies of sit-to-stand and walking motions, and we performed the measurement experiment to verify it. Although the same muscle synergies were utilized, their activation profiles were different. One of the muscle synergies in sit-to-stand motion was also used for lifting up the toe besides rising the hip. In addition, two muscle synergies were activated in the latter time to shift the time of body extension and posture stabilization. On the other hand, humans could successfully start five modules of walking motion from the first step in order to initiate the motion. However, three modules were activated in the transit phase to generate initial momentum necessary for the walking motion.

Our future direction will be investigation of the elderly or the impaired persons, such as Parkinson disease. It is known that those who have Parkinson disease could not initiate the locomotion well. Also, it could be implied that those who had lower scores in timed up and go test cannot activate some of the modules correctly. Investigating these population will clarify the impaired body functions.

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