Effect of Physical Therapy on Muscle Synergy Structure during Standing-up Motion of Hemiplegic Patients

Hiroki Kogami[1], Qi An[1], Ningjia Yang[1], Hiroshi Yamakawa[1], Yusuke Tamura[1], Atsushi Yamashita[1], Hajime Asama[1], Shingo Shimoda[2], Hiroshi Yamasaki[2], Matti Itkonen[2], Fady Shibata-Alnajjar[2], Noriaki Hattori[3], Makoto Kinomoto[3], Kouji Takahashi[3], Takanori Fujii[3], Hironori Otomune[3], Ichiro Miyai[3]

***Abstract*— Stroke patients suffer from declined physical ability, and it is important to analyze rehabilitation intervention and clarify its effect. In this study, the effect of intervention on the standing-up motion of stroke patients is investigated. First, the intervention timing of a physical therapist (PT) is analyzed quantitatively from the muscle activity of upper limbs during therapy. Next, the intervention effect is evaluated based on body kinematics and muscle synergy. In this study, standing-up motion of hemiplegic patients (n = 12) is measured with and without the intervention by a PT. The results show that PTs teach hemiplegic patients the timing of lifting their buttocks during standing-up motion. Furthermore, it has been found that this intervention could improve the standing-up motion, although stroke patients had inadequate muscle synergy structure. In particular, some patients had delayed activation of the synergy and they could only stood up after they moved their center of mass on their feet. However, the intervention by PTs could induce earlier activation of the synergy. Moreover, the intervention could properly shorten the activation duration of muscle synergy for those who had unusually inappropriate longer activation of synergy. These results imply that disordered and inadequate muscle synergy structure can be improved by proper intervention, and this study contributes to the further development of new rehabilitation methodologies.**

I. INTRODUCTION

Many stroke patients have suffered from declined physical ability. In this paper, we quantitatively analyze the intervention of physical therapists (PTs) while they help the patients to stand up. Furthermore, it is evaluated how the muscle synergy structure is changed due to their intervention. Recently, there has been an increase in the number of stroke patients, and several stroke survivors have some degree of paralysis. This paralysis may decrease motor function and degrade the quality of life [1]. In addition, social security expenses could increase. Therefore, it is important to rehabilitate such patients and improve the motor function of people with paralysis.

Various rehabilitation robots have been developed to improve motor function. Horst et al. developed a wearable powered leg orthosis [2]. This device provides assistive force for knee extension and helps in motion. They showed that orthosis may help paralyzed people improve motor function through rehabilitation [3]. Fisher et al. performed rehabilitation using a machine that helps hemiplegic patients walk [4]. This machine uses a harness to help patients walk on a treadmill for rehabilitation. Even though multiple devices have been introduced, it has become more important to understand human motor control theory to fully utilize these devices for effective rehabilitation.

However, the human motion generation mechanism is not well understood yet. The human body is a redundant system in that humans control more muscles than the number of joints. Bernstein proposed the muscle synergy hypothesis to elucidate how human movements are controlled [5]. According to the hypothesis, humans generate motions using a limited number of modules (referred to as synergy). Certain previous studies reported that there were a few synergies in locomotion [6], arm reaching motion [7], and grasp motion [8]. Furthermore, other previous studies have shown that humans controlled each synergy inadequately when they had motor cortical damage [9] and post-stroke damage [10]. These previous studies imply that humans may utilize a smaller number of synergies to control their muscles. Furthermore, it is suggested that they cannot control each synergy well after a stroke.

Our research group has focused on the human standing-up motion since it is an important daily activity. Many studies about standing-up motion have been reported. Some previous researches analyzed the standing-up motion of healthy young and elderly people based on kinematics, center of mass (CoM), and EMG patterns [11-14]. The data in these researches are of great value to evaluate standing-up motion using CoM and EMG. They found that elderly people tend to move their CoM closer to their feet than young people do in order to keep their posture more stable before extending body. We have also discussed the standing-up motion of elderly and young people by using the muscle synergy hypothesis. Our previous studies suggested that the human standing-up motion consists of four synergies [15] and that different strategies of standing-up motion between the young and the elderly could be explained by parameter change of a muscle synergy [16]. Another research studied the standing-up motion of stroke patients and they found that the standing-up motion of stroke patients becomes unstable,

[1]Hiroki Kogami, Ningjia Yang, Qi An, Hiroshi Yamakawa, Yusuke Tamura, Atsushi Yamashita and Hajime Asama: Department of Precision Engineering, Graduate School of Engineering of The University of Tokyo, Tokyo, Japan, kogami@robot.t.u-tokyo.ac.jp

[2]Hiroshi Yamasaki, Matti Itkonen, Fady Shibata-Alnajjar and Shingo Shimoda: Intelligent Behavior Control Unit, BSI-Toyota Collaboration Center, RIKEN Brain Research Institute, Aichi, Japan

[3]Noriaki Hattori, Makoto Kinomoto, Kouji Takahashi, Takanori Fujii, Hironori Otomune and Ichiro Miyai: Neurorehabilitation Research Institute, Morinomiya Hospital, Osaka, Japan

because of the weakness of the affected side and loss of postural control [17]. Our research group intends to explain changes in the standing-up motion of stroke patients using the muscle synergy hypothesis. Moreover, it is not yet known how rehabilitation aims to change this synergy structure and what effect the change in synergy has.

Although the standing-up motion of a patient is improved by physical therapy, it has not yet been fully understood how the intervention by PTs helps in the recovery of a patient. Figure 1 shows a PT helping a patient with the standing-up motion at a rehabilitation hospital. The therapist intervenes on the front side of the distal part of the patient's paralyzed side and the rear side of the pelvis by using his/her upper limbs. A PT intervenes according to the following four phases of standing-up motion [18].

(i) Bend the upper body forward.
(ii) Lift buttocks off the seat.
(iii) Extend the knee and lumbar joint.
(iv) Stabilize the posture.

During the standing-up motion of the patient, the PT pinches the patient's distal front of the affected thigh and posterior pelvis for a certain period to help the movement. In addition, they either pull or push these parts during the movement. However, their movement has not yet been fully understood quantitatively. In other words, it is not clear at which time and in which direction, the PT needs to apply force to the patients.

Although some previous studies mentioned above, including our research, suggested that human movement could be explained from muscle synergies and that hemiplegic patients could not control synergies well, it has not been understood how physical therapy affects the synergy structure of the patients. Therefore, the objective of this study is to investigate how the intervention of a PT affects the muscle synergy structure when hemiplegic patients practice standing-up motion at a rehabilitation hospital. In this paper, we first analyze PT intervention on the standing-up motion of a patient in order to examine the kind of actions performed by PT. This examination is accounted for in Chapter 2. Next, we study the influence of intervention by PT on the kinematics and muscle synergy of the standing-up motion of hemiplegic patients. This investigation is explained in Chapter 3.

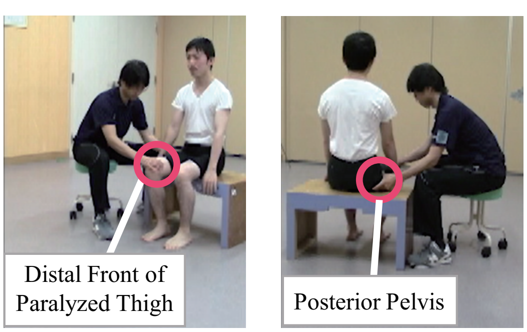


Fig. 1. Intervention of PT. The PT helps the patient stand up by intervention on the knee and posterior pelvis of the patient's affected side.

II. INTERVENTION OF PHYSICAL THERAPIST

A. *Quantitative Analysis of Physical Therapy*

In order to investigate the effect of PT intervention on hemiplegic patients, we first analyze how a PT intervenes in the standing-up motion of a patient. In the physical therapy for standing-up motion, it is known that PTs intervene on the thigh and pelvis of the affected side as shown in Fig. 1; however, it is necessary to clarify further when the PT should intervene on these body parts and in which direction. In particular, this study measures the surface electromyogram (EMG) from the upper limbs of the PT and study their activation timing. In order to avoid disturbance for both PT and the patient, other sensors such as force gloves are not used. Although such sensors measure the force between the PT and patients by attaching a force sensor to PT or patient, the therapy may be disturbed and its effect is reduced. Therefore force sensors or pressure sheets are not used.

As PTs use their upper limbs to assist the standing-up motion of a patient, this study investigates the EMG involved in the flexion or extension of the shoulder, the flexion or extension of the elbow, and the flexion or extension of the wrist, as shown in Fig. 2. The kinematic event of the standing-up motion is measured simultaneously with the EMG to clarify the timing of the intervention. In particular, the time at which the buttocks leaves the sheet is focused, since the characteristics of standing-up motion changes. After the buttocks leave the seat, the patient's posture becomes unstable, and the effect of physical therapy is studied according to this point. Using this EMG, we analyze the activation timing of the flexor and extensor muscles during the sit-to-stand motion.

B. *Experiment*

1) Relationship between EMG of PT and Standing-up Motion: The EMG of the PT was measured to analyze his intervention. As a PT uses his/her upper body when assisting the standing-up motion of hemiplegic patients, the following seven muscles of the upper body on one side were measured: the short abductor muscle (AHB), wrist flexor muscle group (WF), wrist extensor muscle group (WE), biceps brachii (BIC), triceps brachii (TRI), deltoid muscle front part (AD), and posterior deltoid muscle (PD). These muscle positions are shown in Fig. 2. Measurements were taken on the muscles of both limbs. The EMGs of these muscles were measured using a wired surface EMG device (S&ME). The

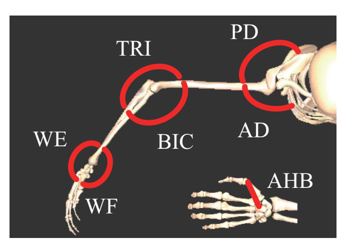


Fig. 2. Measured muscles of the PT. The measured muscles of the PT are muscles related to the abduction of the thumb and flexion or extension of the wrist, elbow, and shoulder joints.

surface EMG was filtered with a band-pass filter of 80–200 Hz and processed according to moving average every 0.3 s. Then, it was normalized and rectified. Normalization was performed using the maximum value of each muscle in one trial to evaluate the activation timing. Additionally, two forceplates were placed beneath the feet and buttocks of the patient to detect the timing when the buttocks leave the chair. In the ten trials, analysis was performed using the motion data for the period between 1.0 s before and 2.0 s after the hip was lifted from the chair.

2) Subject and General Setup: Two PTs who were experts with an experience of over 20 years participated in the experiment. The PTs performed Bobath concept based intervention in the patient's standing-up motion ten times. Twelve hemiplegic patients (ten male and two female, 56.0 $\pm$ 11.6 years old) participated in the experiment. Nine patients had paralysis on the left side, and three patients had it on the right side. The motion functional independence measure (FIM) score was 76.3 $\pm$ 8.6 and the Fugl-Meyer (FM) score was 23.6 $\pm$ 6.0. All the participants were able to stand up by themselves. This study was approved by the Institute Review Board of The University of Tokyo and Morinomiya Hospital.

C. Results

Figure 3 shows the average muscle activity of the PT during the intervention on standing-up motion. The solid line and dashed lines indicate the muscle activity of the arm that intervenes in the thigh and pelvis, respectively. The muscles related to the extension of joints that intervene such as WE (writs extensor), TRI (elbow extensor), and PD (shoulder extensor) are active in the arm that intervenes in the knees before the buttocks leave the seat. These muscles contribute to the extension of the upper limb, which intervenes and pulls the thigh forward. Afterwards, the AHB (thumb abductor) and WF (wrist flexor) are activated in the same limb, when the buttocks leave the seat. This may contribute in pinching the distal thigh and in pushing the knee to induce extension of the joint.

In the muscles of the arm that intervenes in the pelvis, muscle activity, except that for AHB and WE, becomes maximum as the buttocks leave the seat. This result implies that the PT co-contracts both the flexor and extensor of the elbow and shoulder to support the buttocks at the time of leaving the chair. These results show that the PT first intervenes on the thigh of the patient to induce forward movement, subsequently teaches the extension of the knee and lifting up of the hip at the time of the buttocks leave the seat.

III. EFFECT ON MUSCLE SYNERGY STRUCTURE

The previous chapter showed that PT intervenes on the patient mainly before and at the time of the buttocks leave the seat. To investigate the influence of these interventions by PT on the standing-up motion of hemiplegic patients, this study analyzes the change in muscle synergy structure with and without intervention.

A. Method of Assessment of the Standing-up Motion

1) Evaluation of Body Kinematics: The standing-up motion is evaluated based on kinematics. Previous studies analyzed the movement of elderly people and reported that elderly people's center of mass (CoM) and posture of lifting the buttocks off a seat were different [12][13]. Elderly people tend to bend their upper trunk deeper and move their CoM closer to the feet support area before body extension than younger people. Therefore, this study also investigates these characteristics to determine whether the intervention of PT affects these CoM and posture when the buttocks leave the

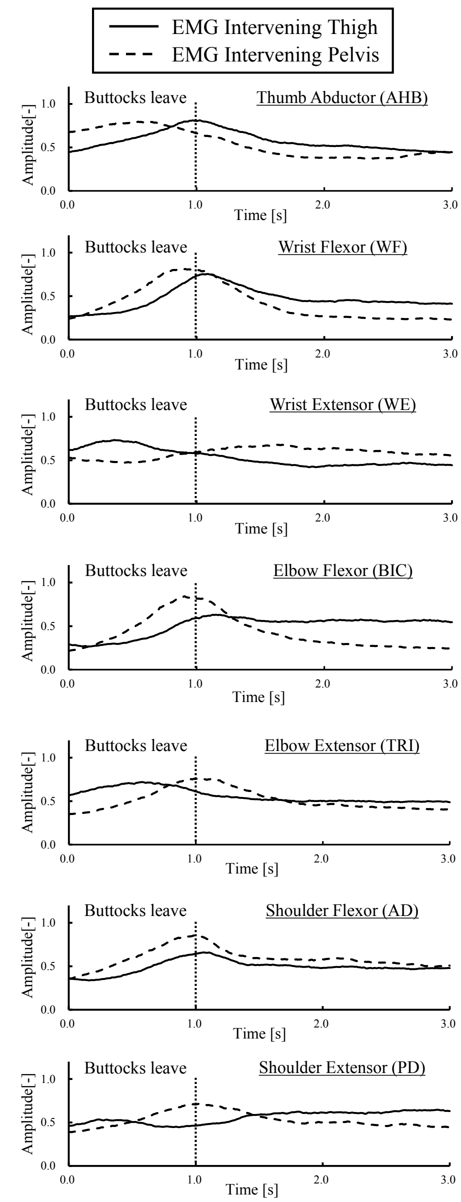


Fig. 3. EMG of the PT. The solid line and dashed lines show the muscle activity of the arm that intervenes in the thigh or pelvis. The vertical dotted line at 1.0 s represents the timing of lifting hip from the chair. The extensor muscles are active and intervenes in the knees before the buttocks leave the seat. Both flexor and extensor muscles are active in the limb to intervening pelvis at the time the buttocks leave the seat.

seat.

2) Evaluation of Muscle Synergy Structure: This study employs the idea of muscle synergy to evaluate the effect of PT intervention. As reviewed in Chapter 1, it is suggested that humans use muscle synergies to control the redundant degree of freedom of muscles. Particularly, our previous studies [16] showed that four muscle synergies could explain the human standing-up motion, and the change in its activation timing explains the different strategies of standing-up motion including that of the elderly. This study evaluates the synergy structure of hemiplegic patients and investigates how it is changed during physical therapy.

In the muscle synergy model, muscle activities are represented by the linear summation of spatiotemporal patterns, as given by (1).

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

where matrices $\mathbf{M}$, $\mathbf{W}$, and $\mathbf{C}$ indicate the muscle activity, spatial patterns, and temporal patterns respectively. Matrix $\mathbf{M}$ contains the muscle activation m_i, as given by (2),

$$\mathbf{M} = \begin{pmatrix} m_1(t_0) & \dots & m_1(t_{\max}) \\ \vdots & \ddots & \vdots \\ m_n(t_0) & \dots & m_n(t_{\max}) \end{pmatrix}, \tag{2}$$

where $m_i(t)(t_0 \leq t \leq t_{\max})$ denotes the activity of the i-th muscle at time t. The spatial pattern matrix $\mathbf{W}$ expresses the relative activity of the muscle and is expressed by (3),

$$\mathbf{W} = \begin{pmatrix} w_{11} & \dots & w_{1k} \\ \vdots & \ddots & \vdots \\ w_{n1} & \dots & w_{nk} \end{pmatrix}, \tag{3}$$

where w_{ij} denotes the activity of the i-th muscle in muscle synergy j. The temporal pattern matrix $\mathbf{C}$ expresses the weighting coefficient of muscle synergy, as given by (4),

$$\mathbf{C} = \begin{pmatrix} c_1(t_0) & \dots & c_1(t_{\max}) \\ \vdots & \ddots & \vdots \\ c_n(t_0) & \dots & c_n(t_{\max}) \end{pmatrix}, \tag{4}$$

where $c_j(t)$ represents the weighting factor of the j-th muscle synergy at time t.

Figure 4 shows the muscle synergy model when three muscle synergies constitute the activities of n muscles. The spatial pattern $\mathbf{W}$ shows the relative muscle activation. The temporal pattern $\mathbf{C}$ shows the relative change in weighting coefficient.

The muscle synergies are extracted from the EMG of subjects using the non-negative matrix factorization algorithm [19]. Firstly, matrix $\mathbf{W}$ is determined randomly. Secondly, matrix $\mathbf{C}$ is obtained using (5). Thirdly, matrix $\mathbf{W}$ is solved using (6). Matrices $\mathbf{W}$ and $\mathbf{C}$ are determined by repeating this procedure. This study employs the same number of muscle synergies (four) as our previous studies [16] to extract synergies from the patients.

$$\mathbf{W}^{\mathbf{T}}\mathbf{W}\mathbf{C} = \mathbf{W}^{\mathbf{T}}\mathbf{M} \tag{5}$$

$$\mathbf{C}\mathbf{C}^{\mathbf{T}}\mathbf{W}^{\mathbf{T}} = \mathbf{C}\mathbf{M}^{\mathbf{T}} \tag{6}$$

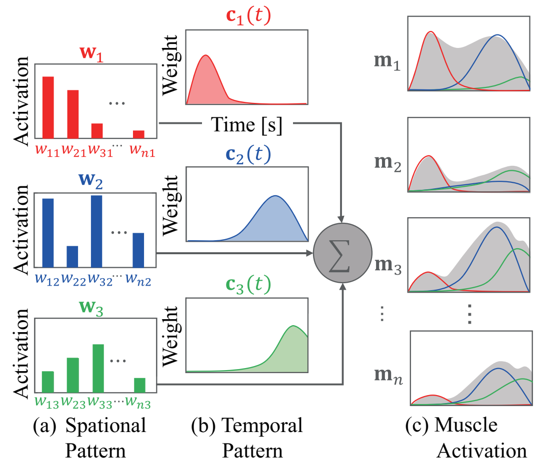


Fig. 4. Muscle Synergy Model. (a) Spatial patterns ($w_{1,2,3}$). It shows the activation of related muscles. (b) Temporal patterns ($c_{1,2,3}$). It shows the weighting coefficient. (c) Muscle activation (gray part). The red, blue, and green lines show the muscle activation made from muscle synergies 1, 2, and 3 respectively.

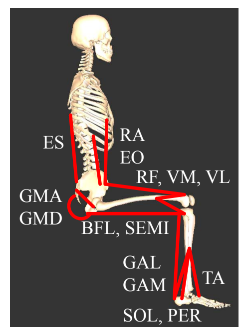


Fig. 5. Measured muscles of the patient. Fifteen muscles related to the standing-up motion such as flexion or extension of the lumbar, hip, knee, and ankle joints are measured.

An et al. showed that four synergies of standing-up motion correspond to the phases of the motion [15]. The synergies mainly contribute to the following motions: bending the upper body (synergy 1), rising the hip from a chair to move forward (synergy 2), whole body extension (synergy 3), and posture stabilization (synergy 4). Among these synergies, synergy 2 is considered to be important because it controls the time the buttocks leave the seat and how far the person moves forward afterwards. Our previous study [16] showed that the characteristic difference between the young and the elderly could be found in this synergy. It has been shown that the muscle synergy 2 is activated later in the elderly. This causes them to move their CoM closer to feet support area and to stand up in a more stable manner than young people do. Moreover, the analysis of PT intervention in Chapter 2 showed that the PT mainly intervenes with the patient at this time. Therefore, this study mainly focuses on synergy 2 to evaluate the effect of PT intervention.

In order to evaluate the change in synergy 2, we first investigate its peak time. As reported in the previous work

[16], delayed activation of muscle synergy 2 generates the stabilization strategy, which is mostly employed by the elderly to first move their CoM towards their feet and then lift up body. On the other hand, young people tend to utilize the momentum generated from bending the upper body to stand up directly. Using these findings, the effect of PT intervention is evaluated to find out if physical therapy improves the standing-up motion of hemiplegic patients.

Furthermore, the activation duration of synergy 2 is evaluated in this study. A previous work [10] investigated the muscle synergy structure of human locomotion in post-stroke survivors. The same number of muscle synergies were extracted from locomotion of stroke patients as healthy subjects and their spatiotemporal structure was compared. Despite similar spatial patterns, they have found that temporal patterns have overlapped activation among synergies of stroke survivors; this results in the merging of synergies. Accordingly, we use the same methodology as previous work [10] to investigate the synergy structure of the patient during standing-up motion. In order to confirm this, VAF is calculated both for stroke patients and healthy elderly people. To evaluate activity duration, it is considered that a synergy is active if the activation level of the temporal patterns of the synergy exceeds its threshold.

In addition, to investigate the effect of PT intervention between two conditions with/without PT intervention, we evaluate whether the intervened motion approaches that of the healthy population. Therefore, the muscle synergy structure of the patient is compared to that of age-matched healthy elderly population as well.

B. Experiment

1) Evaluation of the Exercise and Muscle Synergy: This study investigates the changes in the standing-up motion of patients due to the intervention by PTs to evaluate its effect on the body kinematics and muscle synergy of patients. In order to investigate body kinematics, CoM is calculated based on the body trajectory. A motion capture system (Motion Analysis. Corp.) was used to measure the motion of the body at 100 Hz. Twenty-two optical body coordinates were measured based on the Helen-Hayes marker set. The body trajectory was filtered using a low pass filter at 6 Hz. The CoM was calculated using SIMM (Musculographics, Inc).

Furthermore, the surface EMG was measured at 2,000 Hz to evaluate the muscle synergy structure. Fifteen muscles on the affected side of each patient were measured. These muscles were related to either the flexion or extension of the lumbar, hip, knee, and ankle joints: rectus abdominis (RA), erector spinae (ES), abdominal external oblique (EO), gluteus maximus (GMA), gluteus medius (GMD), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), biceps femoris long head (BFL), semimembranosus (SEM), tibialis anterior (TA), gastrocnemius medialis (GAM), gastrocnemius lateralis (GAL), peroneus longus (PER) and soleus (SOL). These muscle positions are shown in Fig. 5. The surface EMG device (Cometa Corp.) measured the muscle activities of the hemiplegic patients. The surface EMG was filtered with a band-pass filter of 80–200 Hz and processed according to the moving average every 0.3 s. Then, the EMG was normalized in the same manner as the surface EMG was obtained from the PT. Similarly, the surface EMG and body coordinates of healthy elderly people were measured using the same devices.

2) Subject and General Setup: The same hemiplegic patients who participated in the experiment described in Chapter 2 participated in this experiment also. For comparing the two conditions with/without intervention, the same two therapists participated in this experiment as well. In addition, eight healthy elderly people (8 males, 64.4 ± 3.3 years old) participated in this experiment.

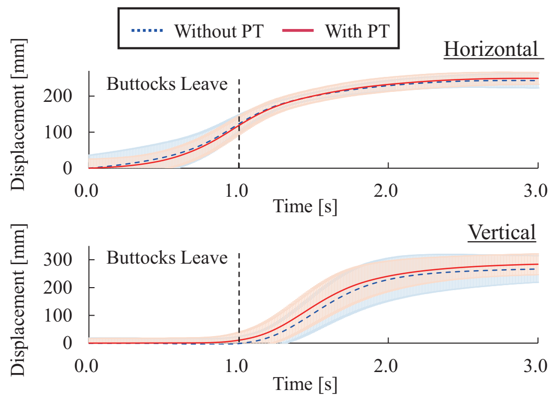
The height of the chair was set to 0.4 m. The patients and the healthy elderly people were asked to stand without using their arms. Ten trials were conducted, in which the participants stood up on their own (referred to as without therapist), and ten trials were conducted with intervention by the PT (referred to as with therapist). In 20 trials, analysis was performed using the motion data of 1.0 s before the hip left the chair and 2.0 s after the hip left the chair. The informed consent was obtained from all the participants. This study was approved by the Institute Review Board of Morinomiya Hospital.

C. Results

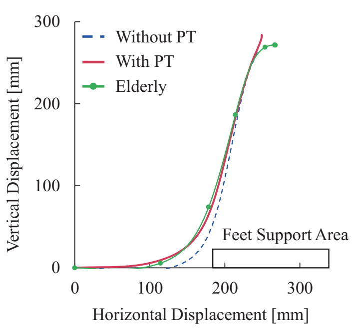
1) Assessment in terms of the Kinematics: Figure 6 (a) shows the trajectory of the average CoM of the patients. The dashed and solid lines indicate the trajectory of the CoM when the patients stood up without and with intervention by the PT, respectively. The solid line with marker indicates the trajectory of the CoM of the healthy elderly people. The figure shows that without intervention, the patients stretch the upper body after getting the CoM closer to the foot, so that they become stable and do not fall from the chair. However, the movement of the CoM of the patients tends to move upward earlier in the case of intervention, and the trajectory of the CoM of the patients resembles that of the elderly people.

Figure 6 (b) shows the posture of a patient when the buttocks leave the seat. The dashed and solid lines represent the cases without and with intervention by the PT, respectively. The figure shows that the posture changes when the buttocks leave the seat, and the patient does not bend the upper body forward considerably when the therapist intervenes. These results indicate that body kinematics of a patient became closer to that of the elderly when a PT intervenes with them.

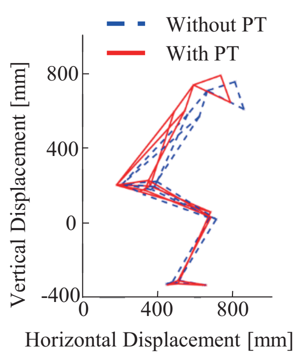
2) Assessment in terms of the Muscle Synergy: The muscle synergy was calculated for each subject when there was no intervention and when there was intervention. When the number of synergies is four, values of VAF were $89.4 \pm 2.0\%$ in heatlhy elderly people and $93.0 \pm 2.2\%$ in stroke patients respectively. Therefore, we decided four synergies are necessary in standing-up motion of stroke patients. The average spatial pattern of the muscle synergy in patients is shown in Figs. 7 (a)-(d). It shows that there is no



(a) Horizontal and vertical displacement of CoM trajectory



(b) Trajectrory of CoM



(c) Posture Difference

Fig. 6. Kinematic Change. (a) shows graphs of average and standard deviation of CoM trajectories for vertical and horizontal directions. The blue dashed and the red solid line represent the cases without and with intervention by PT respectively. (b) shows that the CoM trajectory of patient turns upward owing to intervention by the physical therapist and it approaches healthy elderly people trajectory (green solid line with circles). A square above the x axis represents feet support area. (c) shows that posture of the patient changes when buttocks leave the seat. With PT intervention, the patient does not bend the upper body as much as the patient does without PT intervention. This implies that the patients tend to move upward earlier with the PT assist.

big difference between the patients and the healthy elderly people in terms of the spatial pattern.

On the other hand, it was found that there are mainly two different effects of the intervention by PTs on temporal pattern on muscle synergies shown in Figs. 7 (e)-(l). The first type is the group whose muscle synergy 2 was activated later than that of the healthy elderly when they did not receive intervention. There are six people in that group among the twelve patients.

Figures 7 (e)-(h) show an example of muscle synergy temporal patterns of synergies 1–4 from this group of patients. In the figures, blue dashed lines, red solid lines and green lines with circles indicate time-varying weighting coefficients of synergies from the patient without intervention, the patient with intervention and the healthy elderly people, respectively. From these results, it can be seen that hemiplegic patients have delayed activation of muscle synergy 2 compared to that of the elderly. However, it implies that the activation timing of synergy 2 became earlier when the patient received physical therapy (Fig. 7 (f)).

Similarly, Figs. 7 (i)-(l) represents an example from the other group. It was found that for the patient from this group, the activation of muscle synergy 2 could not be distinguished from that of synergy 3. In other words, the activation duration of synergy 2 was longer for the patient without physical therapy (the dashed blue line in Figs. 7 (j) and (k)). On the contrary, the solid red line in Figs. 7 (j) and (k) shows that muscle synergy 2 was activated separately from synergy 3 when there was intervention by the PT. Although the activation peak time is still later compared to that of the healthy elderly, the activation duration time became closer to that of the healthy elderly people.

Figure 8 (a) shows the average change in peak time between the patients with and without PT intervention from the group in which synergy 2 was activated later (group shown in Figs. 7 (e)-(h)). Figure 9 (b) shows the average change in activation duration time in the patients who are included in the group in which activation duration became longer when they did not receive PT intervention (group shown in Fig. 7 (i)-(l)). On averaging the peak times of 60 trials of six subjects, the value when there was no intervention by PT was 1.28 ± 0.20 s, and when there was intervention, it was 1.16 ± 0.12 s. On performing t-test on these data, it was found that there is a significant difference between when there was no intervention and when there was intervention ($p < 0.05$). The bar graph in Fig. 8 (b) compares the duration for which synergy 2 is active in the group whose graph of synergy 2 are shaped more sharply. Similar to the previous group, when the peak times of 60 trials of six subjects, the value when there was no physical therapist 's intervention was 1.11 ± 0.59 s, and when there was intervention, it was 0.87 ± 0.43 s. Performing t-test on these data, there are a significant difference between when there was no intervention and when there was ($p < 0.05$), when comparing 60 trials of six subjects. From these results, it can be implied that PT intervention could significantly improve the activation time of muscle synergy 2.

IV. DISCUSSION

This study analyzed the PT intervention using muscle activity of their upper limbs while they intervened with the patients. The results show that they mainly pull the thigh of the affected side before the buttocks leave the chair. Afterwards, the PT switched the movement of patient's CoM from forward to upward by extending the knee and supporting the pelvis of the patients. These interventions resulted in different CoM trajectories and body posture as shown in Fig. 6. Furthermore, the PT assists the patient to lift the buttocks using not only the flexor muscles of the elbow and shoulder joint but also the extensor muscles. This stabilizes the upper limbs of the PT and helps to move the center of gravity of the patient upward.

Interestingly, this intervention resulted in change in the muscle synergy structure. In this study, it has been found that the activity of synergy 2 is delayed as well, as reported in

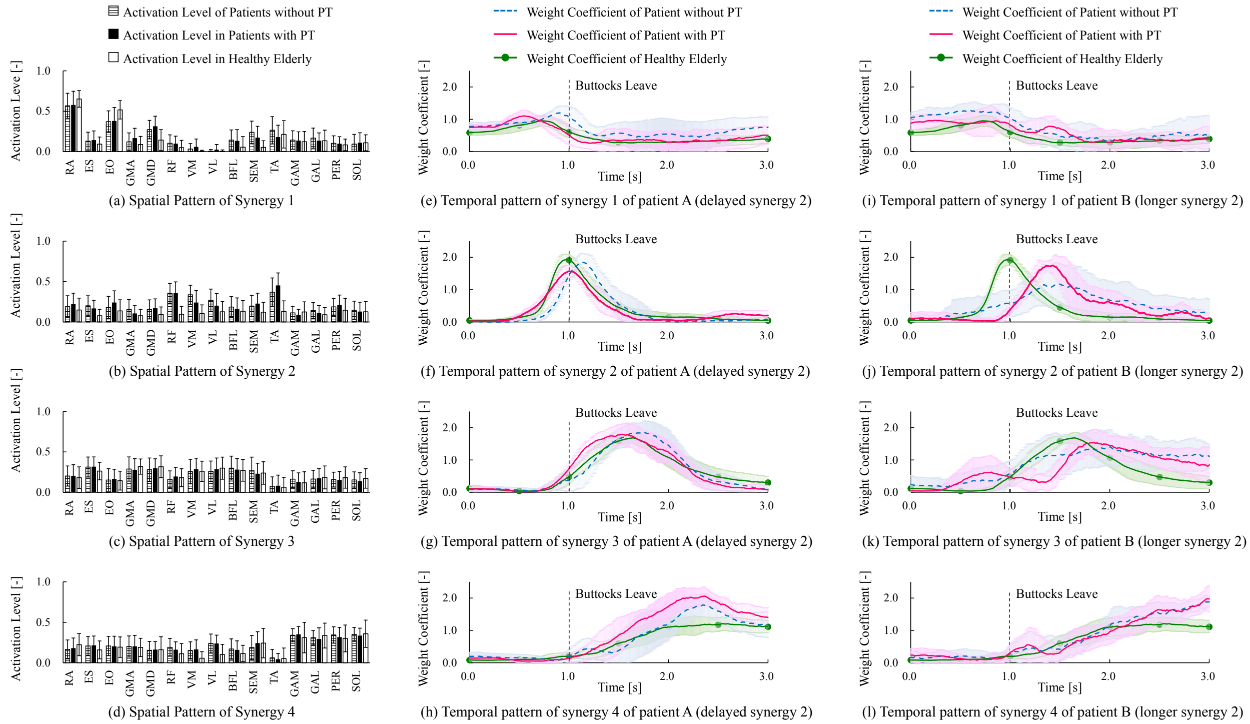


Fig. 7. Spatiotemporal pattern of muscle synergy. (a)-(d) show average spatial pattern of muscle synergy and its standard deviation. In each figure, the bar graph with horizontal lines, the bar graph with filled color, and the bar graph with blank squares show the spatial pattern of patients without PT, that of patients with PT, and that of healthy elderly people. Each figure shows that the spatial pattern of the patients is not much different from that of the healthy elderly people even if the PT does not assist. (e)-(h) and (i)-(l) show average temporal pattern of muscle synergy of patient A who has delayed muscle synergy 2 and that of patient B who has longer activation of muscle synergy 2. Blue dashed line, red sold line, and green solid line with circles respectively show the temporal pattern being extracted form the patient without PT, from those with PT, and from healthy elderly people. When the PT intervenes patient A who is in the group of delayed synergy 2, the peak time of synergy 2 becomes earlier and its activation becomes closer to that of healthy elderly people. On the other hand, activation duration becomes shorter when the PT assists patient B who is in the group of longer synergy.

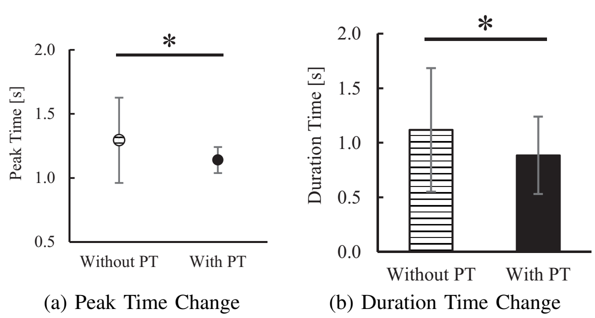


Fig. 8. Change in temporal pattern of synergy 2. (a) shows that there is a significant difference in the peak time of synergy 2. (b) shows that there is a significant difference in the active duration time of synergy 2.

the elderly standing-up motion [16]. However, synergy 2 was found to be more delayed in hemiplegic patients than that in the elderly when their temporal patterns were compared, as shown in Figs. 7 (f) and (j). This implies that hemiplegic patients tend to leave a chair later than the elderly, and they move their CoM closer to feet in order to avoid falling. When a PT intervenes with these patients, the synergy is activated significantly earlier than that without PT. Considering the actions performed on the patient by a PT, this could be caused by teaching the timing of extending the knee joint and pelvis at the time the buttocks leave the seat. The PT could successfully teach the patient to start the upward movement only by intervening in the thigh and pelvis.

On the other hand, the patients in the other group showed the same phenomenon that was reported in a previous study [10], where stroke patients could not activate muscle synergies separately for the locomotion task. Although the patients performed the standing-up motion rather than human locomotion, they could not start and finish each synergy in proper time, and this resulted in merging of several synergies. However, these phenomena could be improved by PT intervention to adjust synergy 2 activity adequately. Similar to the former group, the PT intervenes with the patients to help them notice the correct time at which their buttocks should leave the seat.

The difference among two groups exist in severity of standing-up motion. Particularly, the patients in the group of longer synergy 2 has significantly longer dorxiflexion of the ankle joint than the patients in the group of delayed synergy 2. This phenomenon implies that the patients in the group of longer synergy 2 more dorsiflexed the ankle joint to move their body and CoM closer to feet support area after the time of hip rise. In other words, the patients with longer synergy 2 need more posture stabilization than the other group before extending their body upward. These two groups may reflect different type of compensative strategies that hemiplegic patients can use for standing-up. This difference could be utilized to classify patients into groups and enable clinicians to estimate their future recovery process.

These improvement accompanied with PT intervention emphasizes the importance of correcting the posture and encouraging patients to activate muscle synergies with proper timing. This finding implies the possibility that adding a small force at the proper time could improve muscle synergy activation. However, further analysis and study will be necessary to investigate the mechanism of this improvement.

Another interesting finding is that there is no large difference in spatial pattern between the healthy elderly and the hemiplegic patients. This implies that the module structure of muscle synergy remains even after the stroke occurs. It may be because the module structure exists in the spinal cord as suggested by Takei et al [20] and this structure was not damaged due to stroke. The stroke survivors have less ability to properly plan the motion; however, they still have a modular organization to move several joints. When a PT intervenes with the patients, the patients could again use the sensory input to control their synergies.

These results may contribute to the evaluation of the recovery process during a patient's rehabilitation and the evaluation of PT intervention. It is important to evaluate the standing-up motion of hemiplegic patients in order to perform efficient rehabilitation. Furthermore, this knowledge could be applied to develop assistive or rehabilitation devices for hemiplegic patients. At present, the intervention from PTs is limited to the distal part of the thigh and posterior pelvis, and if the future device can stimulate these body parts similar to the way it is done by a PT, this could possibly improve body function. One of our future studies is to investigate the influence of PT intervention for a longer period. This study mainly investigates immediate effects; however, in order to conduct effective rehabilitation, it is necessary to investigate the effect of PT intervention for a longer duration.

V. CONCLUSIONS

In this study, intervention of PTs was analyzed while they helped hemiplegic patients to stand up. It was found that a PT mainly intervenes in the distal thigh and pelvis before the patient lifts the buttocks off a seat. Moreover, it was found that these interventions could improve the standing-up motion of hemiplegic patients. These patient could either activate a particular synergy earlier to move upward or they could shorten the activation duration of synergy 2 properly.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 26120005, 16H04293 and the Precise Measurement Technology Promotion Foundation (PMTP-F).

REFERENCES

[1] K. Andersen-Ranberg, K. Christensen, B. Jeune, A. Skytthe, L. Vasegaard and J. W. Vaupel, Declining physical abilities with age: A cross-sectional study of older twins and centenarians in Denmark, Age and Ageing, vol. 28, no. 4, pp. 373–377, 1999.

[2] R. W. Horst, A bio-robotic leg orthosis for rehabilitation and mobility enhancement, in Proceedings 31st Annual Conference IEEE Engineering in Medicine and Biology Society, Minneapolis, pp. 5030–5033, 2009.

[3] J. G. Vose, A. McCarthy, E. Tacdol and R. W. Horst, Modification of lower extremity kinetic symmetry during sit-to-stand transfers using a robotic leg orthosis with individuals post-stroke, Biosystems and Biorobotics, vol. 1, pp. 811–814, 2013.

[4] S. Fisher, L. Lucas and T. Thrasher, Robot-assisted gait training for patients with hemiparesis due to stroke, Topics in Stroke Rehabilitation, vol. 18, no. 3, pp. 269-276, 2015.

[5] N. Bernstein, The co-ordination and regulation of movements, Pergamon, Oxford, 1967.

[6] Y. P. Ivanenko, R. E. Poppele and F. Lacquaniti, Five basic muscle activation patterns account for muscle activity during human locomotion, The Journal of Physiology, vol. 556, no. 1, pp. 267–282, 2004.

[7] T. Takei and K. Seki, Synaptic and functional linkages between spinal premotor interneurons and hand-muscle activity during precision grip, Frontiers in Computational Neuroscience, vol. 7, no. 40, 2013.

[8] A. d'Avella, A. Portone, L. Fernandez and F. Lacquaniti, Control of fast-reaching movements by muscle synergy Combinations, Journal of Neuroscience, vol. 26, no. 30, pp. 7791–7810, 2006.

[9] V. C. K. Cheung, A. Turolla, M. Agostini, S. Silvoni, C. Bennis, P. Kasi, S. Paganoni, P. Bonato and E. Bizzi, Muscle synergy patterns as physiological markers of motor cortical damage, Proceedings of the National Academy of Sciences, vol. 109, no. 36, pp. 14652–14656, 2012.

[10] D. J. Clark, L. H. Ting, F. E. Zajac, R. R. Neptune and S. A. Kautz, Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke, Journal of Neurophysiology, vol. 103, no. 2, pp. 844–857, 2010.

[11] M. A. Hughes, D. K. Weiner, M. L. Schenkman, R. M. Long and S. A. Studenski, Chair rise strategies in the elderly, Clinical Biomechanics, vol. 9, no. 3, pp. 187–192, 1994.

[12] M. M. Gross, P. J. Stevenson, S. L. Charette, G. Pyka and R. Marcus, Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women, Gait and Posture, vol. 8, no. 3, pp. 175–185, 1998.

[13] F. Mourey, A. Grishin, P. D'Athis, T. Pozzo and P. Stapley, Standing up from a chair as a dynamic equilibrium task: a comparison between young and elderly subjects, The journals of gerontology. Series A, Biological sciences and medical sciences, vol. 55, no. 9, pp. B425–B431, 2000.

[14] D. Brunt, B. Greenberg, S. Wankadia, M. A. Trimble and O. Shechtman, The effect of foot placement on sit to stand in healthy young subjects and patients with hemiplegia Archives of Physical Medicine and Rehabilitation, vol. 83, no. 7, pp. 924–929, 2002.

[15] Q. An, Y. Ishikawa, S. Aoi, T. Funato, H. Oka, H. Yamakawa, A. Yamashita and H. Asama, Analysis of muscle synergy contribution on human standing-up motion using a neuro-musculoskeletal model, in Proceedings 2015 IEEE International Conference Robotics and Automation, pp. 5885–5890.

[16] N. Yang, Q. An, H. Yamakawa, Y. Tamura, A. Yamashita and H. Asama, Muscle synergy structure using different strategies in human standing-up motion, Advanced Robotics, vol. 31, no. 1-2, pp. 40–54, 2017.

[17] S. W. Chou, A. M. K. Wong, C. P. Leong, W. S. Hong, F. K. Tang and T. H. Lin, Postural control during sit-to stand and gait in stroke patients, American Journal of Physical Medicine and Rehabilitation, vol. 82, no. 1, pp. 42–47, 2003.

[18] P. Riley, M. L. Schenkman, R. W. Mann and W. Andrew, Mechanics of a constrained chair-rise, Journal of Biomechanics, vol. 24, no. 1, pp.77–85, 1991.

[19] D. Lee and H. Seung, Learning the parts of objects by non-negative matrix factorization, Nature, vol. 401, no. 6755, pp. 788–791, 1999.

[20] T. Takei, J. Confais, S. Tomatsu, T. Oya and K. Seki, Neural basis for hand muscle synergies in the primate spinal cord, Proceedings of the National Academy of Sciences, vol. 114, no. 32, pp. 8643–8648, 2017.