Analysis of Contribution of Muscle Synergies on Sit-to-Stand Motion Using Musculoskeletal Model

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Abstract— **Recently, declining physical ability of elderly people has become an extremely important social issue. To improve their daily living activities, the standing-up motion is emphasized in this study as an important daily motion. Synergy analysis is applied to the standing-up motion to extract four important groups of muscle activations (synergies). Furthermore, the effect of synergies on body movement is calculated based on a musculoskeletal model of the human body. Results suggest that the first synergy works as preparation of the motion by pulling the ankle and flexing the hip. The second synergy controls the joint moment of the hip and knee joints to raise the hip and move the center of mass forward. The third synergy controls the ankle joint according to movement of the center of mass. The last synergy stabilizes the posture change from a seated to a standing position. Our findings imply that it is important to train those functional muscle activity to enhance the ability of standing-up motion.**

I. INTRODUCTION

In this paper, the standing-up motion is analyzed based on muscle synergies, and the effects of synergies are elucidated from a musculoskeletal model of the human body.

Recently, the number of elderly people has increased rapidly. Many have suffered from degraded quality of life because of decreased physical ability from aging or disease [1]. In addition, such circumstances impose increased welfare costs or physical and mental burdens to informal care givers [2]. To solve those problems, it is important to enhance the physical activity of elderly people. Particularly, the human standing-up motion is an important motion because many daily activities are distracted or become impossible without the standing-up motion [3].

For assisting the standing-up motion, we previously developed an assistive system that consists of a bed and a support bar system [4]. The system has a force sensor on the bar that encourages system users to use their remaining force to stand up if the measured force from the sensor is less than a threshold value. It generates a fixed trajectory that is extracted from a nursing specialist to lead people if the force is greater than the threshold.

This system can lead people to stand up, but it might strengthen the dependence of users on the system, which implies that functional mobility cannot be fully improved solely by assisting the deficit force or leading people to a certain trajectory. To improve their physical ability, compensation of deficient function alone should not be specifically examined, but the muscles which actuate body joints must be analyzed.

Muscle strength training is known only to be effective when people use their muscles in the same posture as they perform the training [5]. Additionally, it has been suggested that people should train several muscles rather than a single muscle [6]. Results from those previous studies imply that improvement of physical ability depends on the exercise itself (context of the motion) and that it has less effect than using simple muscle strength training.

Therefore, it is necessary to analyze the standing-up motion itself to ascertain the muscle activities included in the motion to enhance physical ability. Developing effective training for functional mobility would be useful if the standing-up motion were divisible into several groups of muscle activations.

Regarding reports of earlier studies that have analyzed human standing-up motions, the standing-up motions can be divided into four phases based on body trajectories and movement of the center of mass [7]. In addition, our previous study [8] extracted groups of muscle coordination from standing-up motions, and their effects on standing-up motion have been identified through a neural network model representing the human musculoskeletal model. However, this neural network model does not consider anatomical characteristics of the human body.

This study measures muscle activation, body trajectory, and reaction force from standing-up motion and elucidates coordinated muscle activations. Our objectives are to clarify relations between extracted muscle activations and joint movement through a musculoskeletal model that employs anatomical characteristics.

II. IDENTIFICATION OF SYNERGY AND ITS CONTRIBUTION TOWARD BODY MOVEMENT

A. Synergy Model

In this study, synergy analysis is used to extract groups of muscle activations from human motion. The idea of synergy analysis was proposed originally by N. Bernstein [9]. It states that people use groups of coordinated several muscle activations (synergy) to control their redundant body: the body has more muscles than the number of controlled joints. As described in this paper, we use a model in which

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muscle activation during motions is approximated by linear summation of several synergies [10].

Equation (1) shows a synergy model used in our study. In the model, d kinds of muscles are observed and muscle activation is expressed as a matrix $\mathbf{M}$. Each column of $\mathbf{M}$ consists of a vector $\mathbf{m}(t)$, which expresses d muscles activation at time t. The element of this vector $m_j(t)$ denotes muscle activation of j-th muscle at time t as in Eq. (2). $T_{\max}$ represents the total time of muscle observation.

$$\mathbf{M} \cong \sum_{i=1}^{N} c^i \mathbf{w}^i (t - t^i), \tag{1}$$

$$\begin{aligned} \mathbf{M} &= [\mathbf{m}(1), \mathbf{m}(2), \cdots, \mathbf{m}(T_{\max})] \\ &= \begin{pmatrix} m_1(1) & \cdots & m_1(t) & \cdots & m_1(T_{\max}) \\ m_2(1) & \cdots & m_2(t) & \cdots & m_2(T_{\max}) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ m_d(1) & \cdots & m_d(t) & \cdots & m_d(T_{\max}) \end{pmatrix}. \end{aligned} \tag{2}$$

This model includes the assumption that the observed d muscle activations are approximated by N synergies $\mathbf{w}^{i=1,2,\cdots,N}$. $\mathbf{w}^i$ comprises vectors $(w_1^i(t), w_2^i(t), \cdots w_d^i(t))$. Each synergy w_j^i is the time-varying synergy activation of j-th muscle in i-th synergy. The actual muscle activation $\mathbf{M}$ is expressed as a linear summation of synergy $\mathbf{w}^i$, with activation coefficient c^i and time delay t^i.

Figure 1 presents an example of the synergy model. In this example, d kinds of muscle activation (Fig. 1(a)) are expressed as the superposition of three synergies $(\mathbf{w}^1, \mathbf{w}^2, \mathbf{w}^3)$. Three synergies have different activation patterns (Fig. 1(c)). In Figs. 1 (a) and (c), the horizontal axis indicates the duration of time in human movement whereas the vertical axis shows the observed muscle activations. People must control their activation coefficient (c^1, c^2, c^3) and time delay (t^1, t^2, t^3) to achieve a complex human motion. Coloured arrows in Fig. 1 (b) show duration of three synergies. The height of each arrow indicate activate coefficients and black arrows show time delays for synergies. It depicts that synergies have sufficient timing to be activated with weighting coefficient.

B. Extraction of Synergies

Decomposition algorithm [11] is used to decompose observed muscle activation to synergy patterns, activation coefficient, and time delay. The algorithm uses multiplicative update rules to minimize the squared errors between observed muscle activation ($\mathbf{M}$) and approximated patterns $(\sum_{i=1}^{N} c_i \mathbf{w}^i (t - t^i))$. The algorithm firstly selects common synergy patterns from several trials. Afterwards, it determines activation coefficient and time delay for each trial.

To ascertain the number of synergies which can sufficiently express human standing-up motion, we change the number of synergies to be extracted to evaluate the accuracy of the model and thereby explain human standing-up motion.

Cross-validation method is used to evaluate the model accuracy. Observed EMG data from several different motions is divided into $(X - 1)$ groups of training data and the

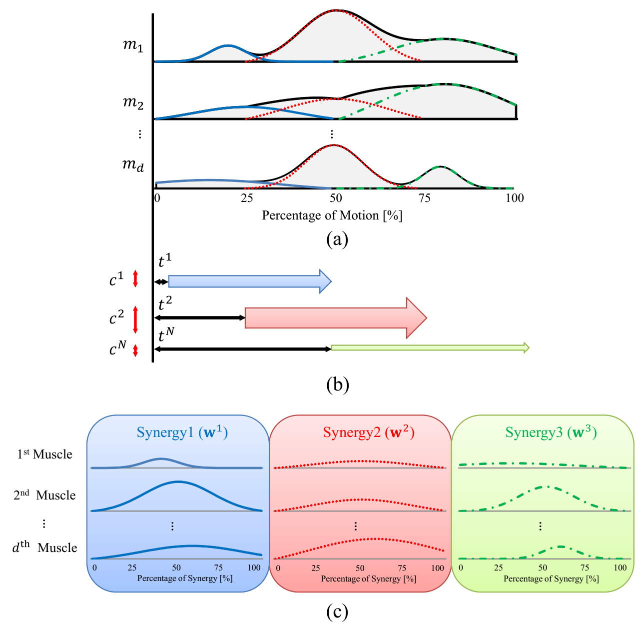


Fig. 1. Synergy Model

remaining 1 group of test data. Synergy patterns are extracted from training data and are evaluated in test data.

The coefficient of determination R^2 is used to evaluate the degree to which the extracted synergies can explain the observed EMG data. R^2 are calculated in different numbers of synergies. A sufficient number of synergies is chosen to represent the observed muscle activation.

To ascertain the optimal number of synergies to be extracted, one-factor repeated measures analysis of variance (ANOVA) is applied to assess the effect of the number of synergies on the accuracy of the model. When there is a statistically significant difference, the Tukey–Kramer test is used for post hoc tests. For this study, the significance level is set as $p = 0.05$.

C. Effect of Synergies toward Body Trajectory

To analyze the effect of extracted synergies toward body joints, the ratio of joint angle change is calculated when extracted synergies are put into a musculoskeletal model. Figure 2 presents our methodology to calculate the change of joint angles.

Human body movement is calculated from the muscular force exerted on the joint and the body posture when force is exerted. Additionally, it is known that muscle tendon force is affected by the muscle length (= joint angles) and the speed of muscle contraction (= angular velocity). Therefore, the inputs of the musculoskeletal model are muscle activation and body posture (joint angle and angular velocity) at time t, from which it is possible to compute the human body posture at the next time $t + dt$. First, initial joint angles and angular velocities are input to the musculoskeletal model. Later, the calculated body posture is put recurrently into the musculoskeletal system to calculate the next posture. The link models with dashed blue lines and solid red lines respectively show the initial posture and movement generated from the input synergy. The change between the initial posture and generated movement by input synergy is examined specifically in this study. As described herein, musculoskeletal model of human lower limbs is developed using SIMM (MusculoGraphics Inc.).

In addition, the starting point of four phases is calculated from the reaction force and body trajectory to elucidate effects of synergies in terms of the kinematics of the human standing-up motion. Figure 3 indicates the four phases defined in the previous study [7].

Phase I is the beginning phase of the standing-up motion; people bend the trunk firstly. The starting point of Phase I is defined as the beginning of the shoulder's horizontal movement. It is determined as the time at which the velocity of shoulder exceeds v_{I}. During Phase II, people rise their hip to transfer the momentum forward. Therefore, the beginning of Phase II is the time when people rise their hip from a seat; it is determined when reaction force from hip becomes less than F_{II}. Phase III is the extension phase to lift up the trunk; the start of Phase III is decided as the time when maximum ankle flexion is observed. The last phase is the stabilization phase, at which time people finish their motion and stabilize the posture. The beginning of Phase IV is determined when the vertical shoulder position becomes the highest.

III. Measurement of Standing-up Motion and Synergy Analysis

A. Setup

In this research, three joints, such as extension and flexion of hip, knee, and ankle are examined to investigate how extracted synergies affect the body trajectory. Figure 4 (a) presents the joint angles considered in this study. Joint angles are defined from the red solid lines, and the direction of red arrows indicates joint flexion. Because the human standing-up motion is performed on the sagittal plane, the movement of only the right body part is specifically examined.

Specifically regarding those muscles which actuate the hip, knee, and ankle joints, eight muscles are measured. Figures 4 (b)–(c) present a view of the measured muscles from front and back views: biceps femoris (BF), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), semitendinosus (SE), tibialis anterior (TA), peroneus longus (PL), and the gastrocnemius (GAST). Those muscles are chosen based on the anatomical viewpoint according to whether those muscles affect body joints. Following are the flexion and extension of each joint and muscles connected to those joints.

- Hip Extension: BF
- Hip Flexion: RF, VL, VM

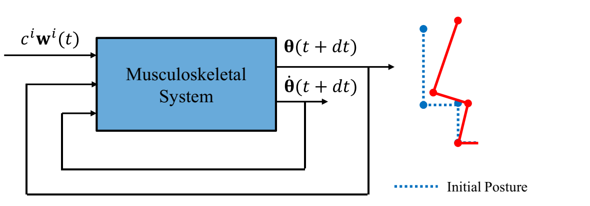
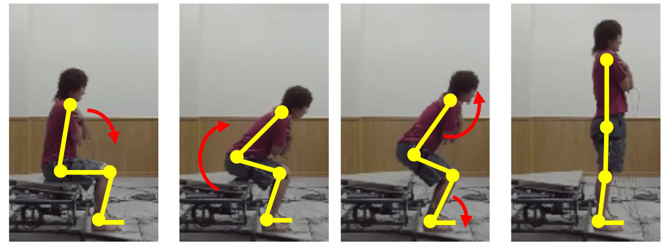
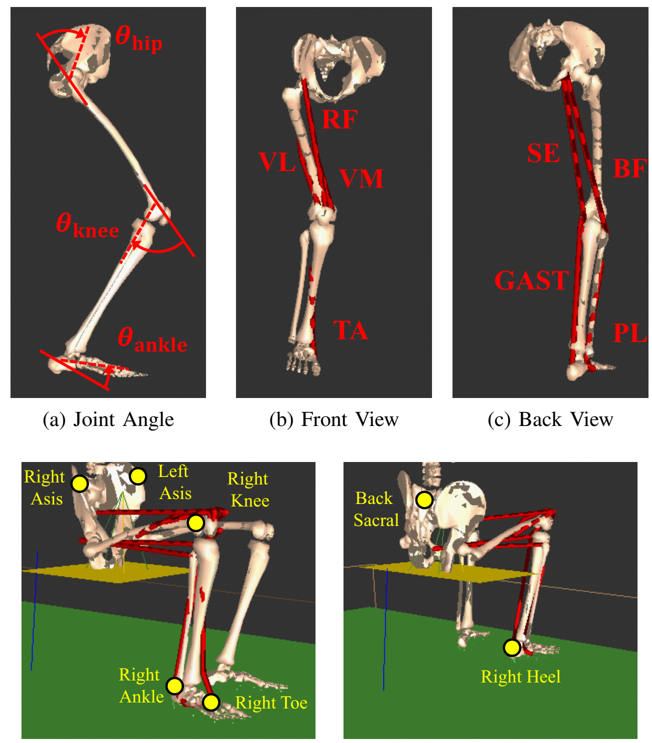


Fig. 2. Computation of Joint Angle from Musculoskeletal System



(a) I (b) II (c) III (d) IV

Fig. 3. Phase Clarification in Standing-up Motion



(a) Joint Angle (b) Front View (c) Back View

(d) Front View (e) Back View

Fig. 4. Musculoskeletal System

- Knee Extension: RF, VL, VM
- Knee Flexion: BF, SE, GAST
- Ankle Extension: TA
- Ankle Flexion: PL, GAST

Figures 4 (d)–(e) show measured body positions to calculate the body trajectory of the standing-up motion. In all, seven markers were attached to the right and left as is, back sacral, right knee, ankle, heel, and toe. Joint angles and the center of mass are also calculated using SIMM. The segment length of our musculoskeletal model is ascertained by a static pose in which people stand still and spread their arms wide.

B. Participants

One healthy man participated in our experiment (26 years old, 1.77 m height, 79 kg weight). Before the start of the experiment, consent was obtained in compliance with the ethics committee of the Graduate School of Medicine and Faculty of Medicine, The University of Tokyo.

C. Procedure

In this study, people were asked to stand up from a chair that was 0.45 m high and which had neither an arm rest nor a backrest. A subject was asked to place feet shoulder-width apart and to have arms crossed in front of the chest in order not to use their arms to stand up. The subject was asked to stand-up in comfortable speed. In our measurement experiment, 72 standing-up motions were obtained.

D. Signal Processing

To perform synergy analysis, all EMG data were subtracted by the mean and filtered using 200 Hz low-pass and 5 Hz high-pass filters. In addition, all data were rectified and a smooth filter was applied as in Eq. (3). In the equation, $m_i(t)$ is the i-th measured muscle activation and $m'_i(t)$ is the filtered data. Later, data were downsampled to 200 Hz. EMG data were normalized to 0–1 based on maximum voluntary contraction of each muscle.

$$m'_i(t) = \frac{\sum_{t'=-50}^{t'=49} m_i(t-t')}{100}. \quad (3)$$

Body trajectory data was obtained in 200 Hz. For the post process of body trajectory data, spline interpolation was applied in case of data gap. Afterwards, 10 Hz low-pass filter was applied. Reaction force was measured in 64 Hz and was filtered with 25 Hz low-pass filter and resampled to 200 Hz.

IV. Results

A. Data Analysis

Synergy analysis was performed on observed 72 standing-up motions. The obtained data were divided randomly into six groups with 12 data (five training groups and one test group). The coefficient of determination was computed for test group in different numbers of synergies (1–7) extracted from the training group. This cross validation method was repeated seven times for seven test groups. After the number of synergies was determined, the extraction of synergies was performed for all 72 data.

B. Determination of Number of Synergies

The mean of the coefficients of determination is calculated from obtained 72 trials of standing-up motion. Figure 5 portrays a change of mean and standard deviation according to the numbers of synergies. According to the results of ANOVA, a significant difference was found in the coefficient of determination among numbers of extracted synergies (p <0.05; F=248.3). When a post-hoc test was conducted for the neighboring number of synergies, a statistically significant difference was found between one and two, two and three, and three and four, which demonstrates that the coefficient of determination is saturated when the number of synergy is four. Therefore the number of synergies to be extracted is chosen as four.

C. Extraction of Synergies

Table I presents average time delay and its standard deviation of extracted four synergies. Activated muscles in extracted synergies, and its effect on joints are shown in Fig. 6. Solid red lines and dashed yellow lines respectively show extension and flexion of the joint.

The first synergy ($\mathbf{w}_1$) starts from the early time of the standing-up motion (0.36±0.68 s); the biceps femoris (BF), vasutus medialis (VM), tibialis anterior (TA), peroneus longus (PL) are activated. The second synergy ($\mathbf{w}_2$) begins at the middle of the motion (0.80±0.28 s); the rectus femoris (RF), biceps femoris (BF), vastus lateralis (VL), vastus medialis (VM), peroneus longus (PL) are activated. The third synergy ($\mathbf{w}_3$) also starts at the middle of the motion (0.94±0.29 s); the biceps femoris (BF), vastus lateralis (VL), vasuts medialis (VM), tibialis anterior (TA) are activated. The fourth synergy ($\mathbf{w}_4$) begins at the last of the motion (1.39±0.66); the biceps femoris (BF), semitendinosus (SE), gastrocnemius (GAST), peroneus longus (PL) are activated.

D. Phase Division

Obtained data are divided into four phases based on the definition of the previous study [7]. In this study, v_{I} and F_{II} were set to 0.1 m/sec and 10 N. Table II presents the average start time of each phase and its standard deviation.

E. Change of Joint Angle from Synergy

Table III shows changes of joint angles when extracted synergies are put into the musculoskeletal model. Positive and negative values respectively denote the direction of extension and flexion. $\mathbf{w}^1$ mainly flexes the hip, and extends knee and ankle joints. $\mathbf{w}^2$ extends the hip and knee joints, and flexes ankle joint. $\mathbf{w}^3$ and $\mathbf{w}^4$ extends all joints.

Figure 7 shows examples of muscle synergies and measured body movement in the standing-up motion. Figure 7 (a) portrays time series of hip, knee, and ankle joints, and the center of mass in horizontal and vertical directions. Four

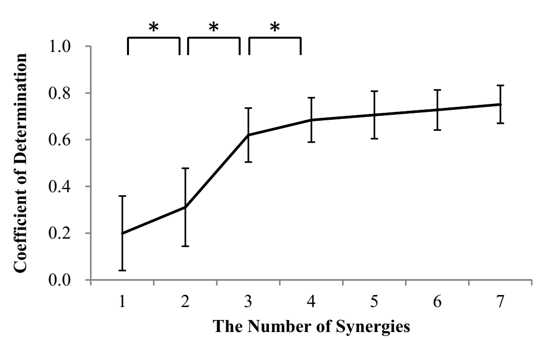


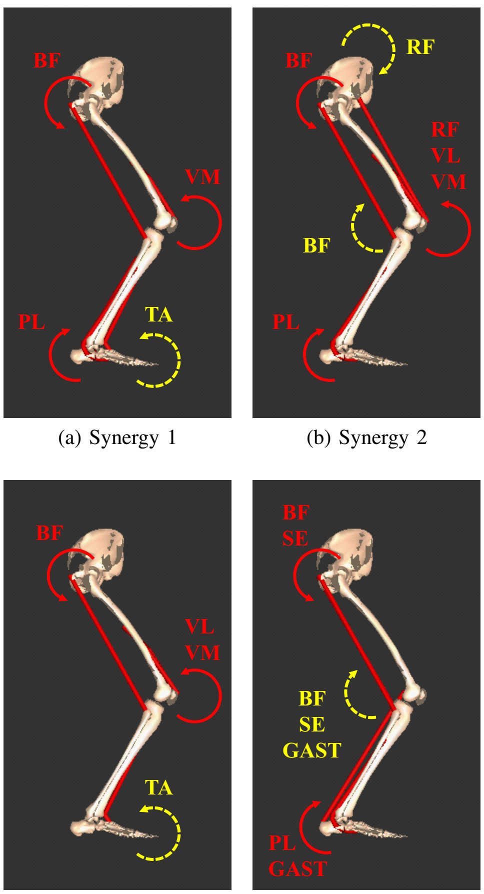
Fig. 5. Determination of Synergies Number

TABLE I
TIME DELAY FOR EACH SYNERGY

	$\mathbf{w}_1$	$\mathbf{w}_2$	$\mathbf{w}_3$	$\mathbf{w}_4$
Mean Time Delay [s]	0.36	0.80	0.94	1.39
STD Time Delay [s]	0.68	0.28	0.29	0.66

vertical solid lines in the figure show the start of each phase. The solid red line, dashed black line, and green broken line respectively show angles of the hip, knee, and ankle. The blue line with blue circle markers shows the change of the center of mass in the horizontal direction. The blue line with blue triangle markers shows the change of the center of mass in the vertical direction. The left y axis of the graph shows the joint angles [deg], the right y axis shows the center of mass [m], and the x axis shows time [s].

Figure 7 (b) represents extracted synergies in a square whose rows are time-series of different muscle activation. The abscissa shows time. Activations are expressed in gray scale: the brighter, the more activations are observed. Figure 7 (c) shows the measured muscles. Each synergy has time delay and the order of synergies start is $\mathbf{w}^1$, $\mathbf{w}^2$, $\mathbf{w}^3$, and $\mathbf{w}^4$ in this example.



(a) Synergy 1 (b) Synergy 2

(c) Synergy 3 (d) Synergy 4

Fig. 6. Extracted Synergies

TABLE II
START TIME OF EACH PHASE

	I	II	III	IV
Mean Start Time [s]	0.78	1.1	1.4	2.2
STD Time Delay [s]	0.16	0.17	0.17	0.22

TABLE III
CONTRIBUTION OF EACH SYNERGY

	$\mathbf{w}_1$	$\mathbf{w}_2$	$\mathbf{w}_3$	$\mathbf{w}_4$
Hip [%]	-6.5	112.5	92.7	66.8
Knee [%]	30.9	74.0	125.8	53.0
Ankle [%]	20.5	-296.0	63.9	44.1

V. DISCUSSION

The first synergy $\mathbf{w}^1$ begins before Phase I, which is the start of standing-up motion defined by results of a previous study [7]. Particularly, the result of both activation agonist muscle (TA) and antagonistic muscle (BF) shows that they pull their ankle by stiffening the ankle joint. In addition, this is the only synergy which flexes the hip joint. It starts to bend before the predicted movement.

The second synergy $\mathbf{w}^2$ has more activations than other synergies; it continues from the middle of Phase I to Phase III. This synergy controls joint moment of hip and knee by activations of both agonist and antagonistic muscles. In addition, extension of hip and knee joints raises the hip to move the center of mass forward.

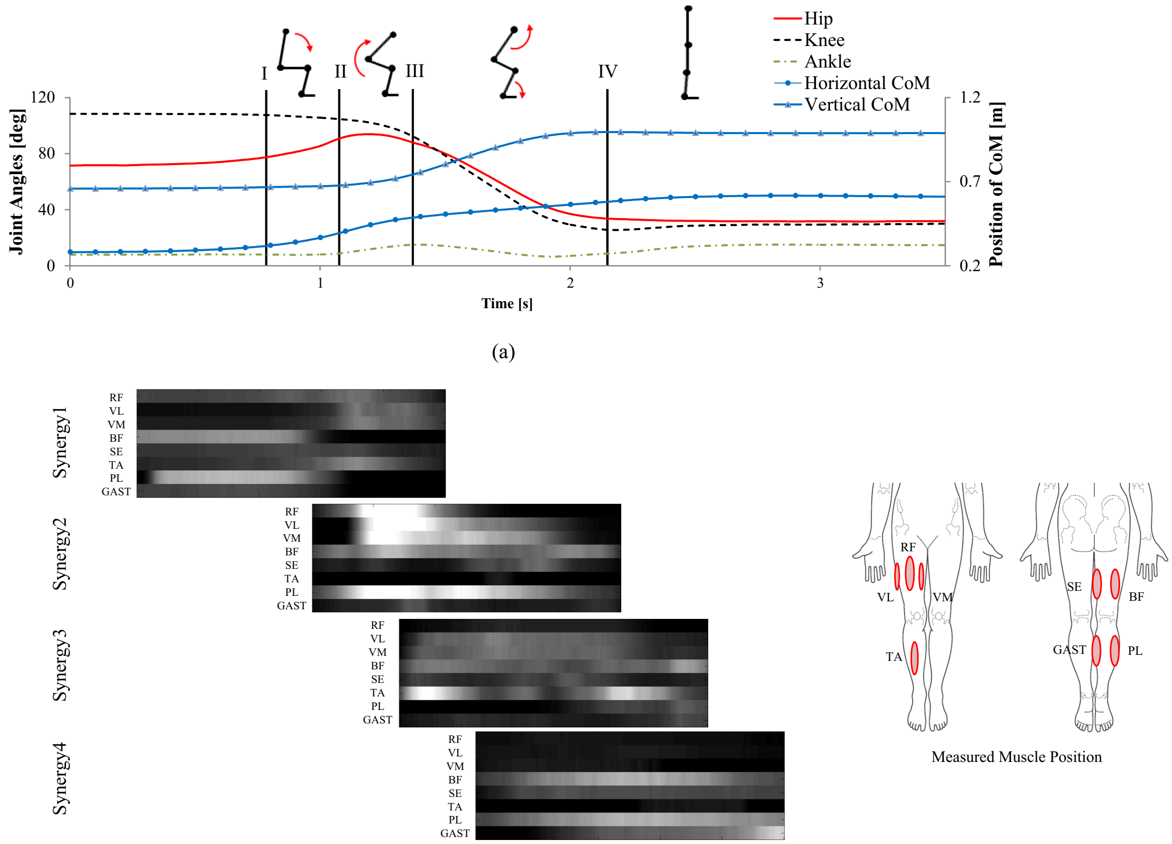
The third synergy flexes the ankle joint. It is presumed to control the movement of the center of mass from Phase II to Phase III. At the same time, it extends the hip and knee joints to lift up the upper body.

The last synergy continues from Phase III to IV to extend all joints, but its activations are fewer than those of the third synergy $\mathbf{w}^3$. That fact implies that this synergy stabilizes the posture rather than lifting up the upper body. In Phase IV, posture must be stabilized against the vertical movement of center of mass from a seated to a standing position.

These four synergies suggest an important training methodology for standing-up motion. If people need to train the first motion preparation and hip bending motion, they need to enhance co-activation of back of thigh (BF) and front shank (TA). Similarly, the second synergy implies the necessities to train front thigh to rise their hip. In order to train body extension, simultaneous activation of front thigh (VL and VM) and front shank (TA) will be needed. On the other hand, enhancement of antigravity muscles (PL and GAST) is essential for training of posture stabilization. Based on synergies which are related to functional body movement of standing-up motion, muscle training strategy is proposed.

Although synergies were extracted only from one subject, the synergy analysis is applicable to several subjects to elucidate their similarities and differences. In this methodology, joint movements were calculated without consideration of the reaction force to the foot, but the reaction force was included to investigate the motion of pulling of the ankle or movement of the center of mass to their feet.

Our study used eight muscles to express standing-up motion due to the constraints that only outer muscles are measurable by surface EMG, although other important muscles affect the motion or body trunk, such as the psoas muscles. However, those inner muscles are barely measurable from surface EMG sensors. Therefore, the future direction of our study is to employ an estimation algorithm to compute



(a)

(b)

(c)

Fig. 7. Standing-up with Synergies

the activation of inner muscles from kinematic data.

Additionally, the standing-up motion will be measured under various circumstances. This study measures the motion in the same circumstances, but it is known that movement speed, chair height, and the usage of arm and back rests will influence the motion. Therefore, the synergy analysis will be applied to other data recorded under different circumstances to elucidate variant and invariant structures of synergies.

VI. Conclusions

Four synergies in standing-up motion were extracted and its effects on each joints were calculated. Those results suggest that each synergy works as motion preparation, rising hip and movement of center of mass forward, flexion of the ankle joint and lifting up upper body, and stabilization of posture after standing-up motion. In addition, muscle co-activation included in extracted synergies implies new training strategy for improvement of standing-up motion.

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