Muscle Synergy Analysis of Human Standing-up Motion with Different Chair Heights and Different Motion Speeds

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***Abstract*—Although standing-up motion is an important activity of daily living, it remains unclear how people perform the motion in different situations. As described in this paper, muscle synergy analysis is applied to standing-up motions performed at different circumstances, such as two different heights and at three different speeds. Results elucidated three invariant groups of synchronized muscle activations: The first synergy pulls the ankle and raises the hip. The second synergy extends the upper body. The third synergy stabilizes posture. Results also show that people controlled the activation coefficient of each synergy differently during all motions. The slower the standing-up motion is, the longer each synergy activates to adapt to the slower motion speed. Results of this study show that people use the same group of synchronized muscle activation and only control the activation coefficient to achieve adaptive standing-up motion.**

***Index Terms*—Standing-up Motion, Synergy Analysis**

I. Introduction

In this paper, we analyze human standing-up motion to elucidate how people stand up in different situations such as different chair heights and different speeds. Recently, the rapid aging of the population has brought many difficulties to our society. Many elderly people have suffered from degraded quality of life attributable to impaired physical capabilities [1].

To improve the situation, standing-up motion is targeted as among the most important daily activities [2]. In physical therapy, much muscle training has been conducted to strengthen lower leg muscles. However, the improved strength of single muscles is known not to improve physical ability fully [3].

Especially, because the standing-up motion includes movement of the whole body, it is important to train to move several muscles simultaneously. Therefore, finding important coordinative muscle movements from the standing-up motion is expected to be useful for developing a training methodology.

For daily mobility, the most important function is generating adaptive motion depending on individual situations. Focusing on the standing-up motion, people do not always stand up from the same chair or at the same speed. The standing-up motion is determined by the surrounding environment or a person's own preferences. To develop a training methodology, it would be important to identify what kinds of muscle movement are necessary to stand up in various environments.

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Our recent study revealed that people have three important groups of synchronized muscle activations that they use to achieve the standing-up motion [4]. In addition, the difference between young people and elderly people was inferred as the first hip bending motion and posture stabilization. However, in the previous study, the motion was measured only in the same environment with the same chair height. The motion speed was not controlled. Consequently, it has not been fully analyzed yet whether those groups of synchronized muscle activations are changed or how they are used in different environments.

Regarding analysis of the standing-up motion, the former study revealed that lower height of chair increases moment and angular velocities of knee and hip joint and induces foot position change [5]. Results showed that faster motion speed results in the increase of hip flexion, knee extension, and ankle dorsiflexion joint moments [6]. In those studies, it has not been clarified yet how people coordinate their muscles to achieve the standing-up motion given different chair heights or speeds.

In terms of muscle coordination, another study showed that onset of muscle activity is consistent in two different feet positions although forward feet placement increases the movement duration, displacement, and the velocity of the trunk [7]. In this study, we specifically examine two different conditions of standing-up motions: external and internal conditions. One condition is different chair height, which is determined by the external environment. The other is the different motion speed, which is decided by people themselves.

Our objective in this study is to analyze how people perform adaptive standing-up motion from different chair heights and with different motion speeds. Muscle synergy analysis is performed to elucidate synchronized muscle activation and their activation coefficient.

II. Methods

A. Synergy Analysis

As described in this paper, the muscle synergy analysis is used to elucidate coordinated muscle activation. The idea of synergy (synergy hypothesis) was originally suggested by Bernstein to explain how humans achieve adaptive motion with their redundant body [8]. The hypothesis is that people have a set of implemented motor primitives and that they only control their activation rate to achieve the motion.

Based on the synergy hypothesis, recent muscle synergy analyses have been introduced to explain variant motions with groups of synchronized muscle activation (synergy) and time-series of activation coefficients through the motion (activation profile) [9]. The model includes the assumption that that muscle patterns (EMG) can be expressed as a linear summation of groups of synergies as in eq. (1). Because people have specific synergies ($\mathbf{w}$), they must control the activation profile ($\mathbf{c}$) to achieve the specific motion.

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

In the equation, the matrix, $\mathbf{M}$, represents a time-series of observed muscle activation (eq. (2)). The i-th row represents a sequence of i-th muscle activation in a whole motion ($i = 1, 2, \cdots, n$). Each column presents a set of muscle activations at different times $t (1 \leq t \leq T_{\max})$.

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

Furthermore, $\mathbf{W}$ and $\mathbf{C}$ express synergies and their activation profile (eq. (3–4)). Each column of the synergies $\mathbf{W}$ represents each synergy ($\boldsymbol{w}^{j=1,2,\cdots,N}$). Moreover, $\boldsymbol{w}^j$ has n synchronized activation levels for observed n muscles ($w^j_{i=1,2,\cdots,n}$). Each row of the activation profile $\mathbf{C}$ represents an activation profile ($\boldsymbol{c}^{j=1,2,\cdots,N}$) corresponding to each synergy ($\boldsymbol{w}^j$). $\boldsymbol{c}^j$ comprises time-series of activation coefficients ($c^j(t)$) at time $t (1 \leq t \leq t_{\max})$. In this model, the synchronized activation level of each synergy is the same during the motion. People need to control an activation coefficient of each synergy in the entire period of motion.

$$\mathbf{W} = [\boldsymbol{w}^1, \boldsymbol{w}^2, \cdots, \boldsymbol{w}^N] = \begin{pmatrix} w^1_1 & w^2_1 & \cdots & w^N_1 \\ w^1_2 & w^2_2 & \cdots & w^N_2 \\ \vdots & \vdots & \ddots & \vdots \\ w^1_n & w^2_n & \cdots & w^N_n \end{pmatrix} \tag{3}$$

$$\mathbf{C} = [\boldsymbol{c}^1, \boldsymbol{c}^2, \cdots, \boldsymbol{c}^N]^T = \begin{pmatrix} c^1(1) & \cdots & c^1(t) & \cdots & c^1(T_{\max}) \\ c^2(1) & \cdots & c^1(t) & \cdots & c^2(T_{\max}) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ c^N(1) & \cdots & c^N(t) & \cdots & c^N(T_{\max}) \end{pmatrix} \tag{4}$$

Figure 1 presents an example by which muscle activation is constructed from a linear summation of three synergies. The right part of the figure shows muscle activation at time $t, t+1, \cdots$. In the middle of the figure, three muscle synergies exist ($\boldsymbol{w}_1, \boldsymbol{w}_2, \boldsymbol{w}_3$), which have different synchronized muscle activation. To achieve the specific motion, people control an activation coefficient of each synergy at each time ($\boldsymbol{c}_1, \boldsymbol{c}_2, \boldsymbol{c}_3$ portrayed in the left part of the figure).

As described in this paper, we decompose the observed muscle activation into groups of synchronized muscle activation (synergy) and time series of activation coefficient (activation profile). The non-negative matrix factorization [10] is applied to ascertain $\mathbf{W}$ and $\mathbf{C}$ to minimize the squared error between observed muscle patterns ($\mathbf{M}$) and reconstructed patterns with synergies and activation profile ($\mathbf{WC}$). The coefficient of determination, R^2, is used to evaluate how much the extracted synergies can explain observed EMG data.

Synergies and activation profiles are extracted from every standing-up motion, and R^2 is calculated for individual motion. Average R^2 for every participant in different experimental conditions are used to evaluate how many synergies are sufficient to explain the human standing-up motion. In this study, we use the same threshold (90%) as those used in a previous study [11] to determine the number of synergies. Synergies are assumed to be sufficient if extracted synergies and activation profile can explain more than 90% of observed data.

As described in this paper, six lower limb muscles were measured from surface EMG. Each muscle is chosen based on whether muscles control the ankle, knee, and hip joint movement. Figure 2 (a) shows the measured muscles: rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), tibialis anterior (TA), peroneus longus (PL), and gastrocnemius (GAST).

B. Condition of Standing-up Motion

1) Chair Height: Two different chair heights are used. The chair heights are decided based on the shank of each participant. 100% or 50% of the shank is used as the chair height. In this paper, 100% of the shank is defined as a normal height and 50% of the shank is defined as a lower height.

2) Speed of Motion: A metronome is used to control the speed of the standing-up motion of people. Three conditions of speed are used in this study. Participants were asked to start their standing-up motion when they hear the beep sound, and to try to finish their motion at the next beep sound. Three different tempos are used for this study: 20, 40, and 80 beats per minute (BPM).

C. Data Measurement

EMG data are obtained at 1000 Hz. Measured EMG data are filtered with 10 Hz high-pass filter and 200 Hz low-pass filter.

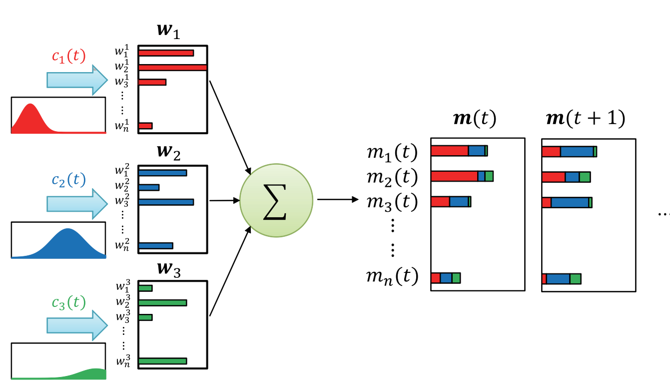


Fig. 1. Synergy Model.

The smooth filter is applied to the data as in eq. 5, where $m_i(t)$ is the muscle activation of i-th muscle at time t and $m'_i(t)$ are the filtered data. 0.1 s of the data are used to average data.

$$m'_i(t) = \frac{\sum_{t'=-50}^{t'=49} m_i(t+t')}{100} \tag{5}$$

Force data are obtained from the hip and feet at 64 Hz. Then they are also filtered with a 25 Hz low-pass filter. To compare EMG data and force data, linear interpolation is applied to the force data to be the same length of EMG data.

To compare different trials of standing-up motions of subjects, the point of hip raising is specifically examined. Only EMG data that are 1.0 s prior to and 1.5 s posterior to hip rising are used for this study. The time of hip rising is determined as that when the reaction force from their hip is less than 1 N.

D. Experiment

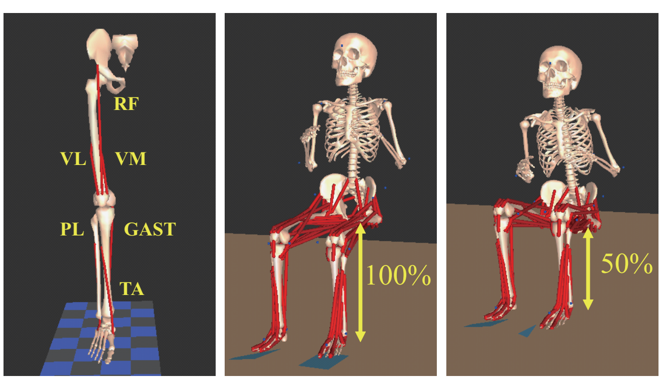
1) Experimental Procedure: Our experiment comprises 12 separate trials. From the first trial to the sixth trial, participants stand up from the normal chair height. The tempos of the metronome were respectively set as 80, 40, 20, 20, 40, and 80 BPM. Participants stand up from the lower chair height in the remainder of the trials (from seventh trial to twelfth trial). Similarly, the tempo of the metronome is also set as 80, 40, 20, 20, 40, and 80 BPM in trials with lower height.

Every trial continues 90 s, and participants are asked to repeat standing-up and sitting down alternately in the same position. People are given a verbal signal to indicate the time at which they can either stand up or sit down. Thereby, we confirmed that all standing-up and sitting motions are divisible.

During each trial, the tempo of the metronome is played continuously. Participants were asked to start the motion whenever they felt comfortable after our verbal signal.

For the experiment, participants put their arms in front of their chest to prevent the use of arms for the motion. Before performing every standing-up motion, the ankle angle is set as approximately 85 deg.

2) Participants: In all, three young healthy people, s1–3, participated in our experiment (2 male, 1 female; 28.7±2.51 years old). The study was conducted with approval by the Institutional Review Boards (IRB) of the University of Tokyo, and all participants provided written informed consent.



(a) Muscles (b) Normal Height (c) Lower Height

Fig. 2. Experimental Conditions.

TABLE I
NUMBER OF OBSERVED MOTIONS.

		s1	s2	s3
Normal Height	20 BPM	18	15	10
	40 BPM	16	14	12
	80 BPM	21	26	16
Lower Height	20 BPM	17	12	14
	40 BPM	20	14	18
	80 BPM	31	18	18

3) Experimental Setup: A BioLog DL2000 (S&ME, Inc.) device was used to measure EMG data from the lower leg of subjects. EMG sensors have an amplifier inside. The distance between electrodes was 0.02 m.

Six-axis force sensors (Nitta Corp.) were used to measure the reaction force from the hip and feet. Three force sensors were placed in each corner of the triangular force plate.

III. RESULTS

A. Determining the Number of Synergies

From our experiment, about 10–30 standing-up motions were observed in each experimental condition of three participants. Details of the numbers of observed motions are presented in Table I.

Figure 3 (a)–(f) shows changes of coefficients of determination in different experimental conditions. In each graph, the blue solid line represents the average coefficient of determination of s1, black dashed line shows those of s2, and a red solid line with red circle markers shows those of s3.

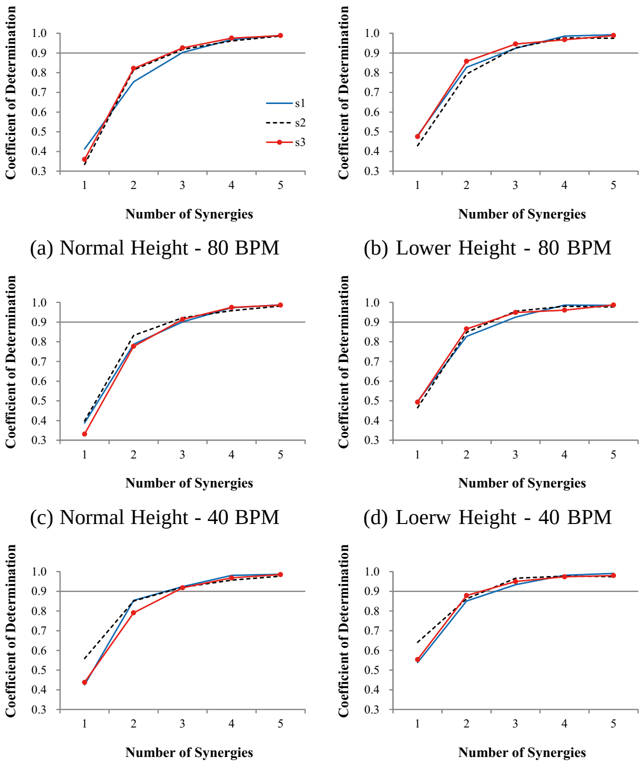
In all experimental environments, results of the coefficient of determination indicate that three synergies are sufficient to explain more than 90% of observed EMG data from all subjects. Therefore, the number of synergies to be extracted is set to three in this study.

B. Synergy Activation

Three extracted synergies ($\boldsymbol{w}_1, \boldsymbol{w}_2, \boldsymbol{w}_3$) were extracted from all experimental conditions. Figures 4 and 5 show synchronized activation levels of respective muscles included in every set of synergies. In both graphs, (a) indicates the first synergy ($\boldsymbol{w}_1$), (b) illustrates the second synergy ($\boldsymbol{w}_2$), and (c) shows the third synergy ($\boldsymbol{w}_3$). Figure 4 portrays synergies extracted from trials of three different motion speeds (20/40/80 BPM) performed on the normal chair height. Figure 5 indicate synergies from three different motion speeds performed on the lower chair height. In both graphs, black, white, and gray bars respectively show synchronized activation levels calculated from s1, s2, and s3. Error bars represent standard deviations of individual muscle activation.

In $\boldsymbol{w}_1$, the rectus femoris and tibialis anterior are more activated than other muscles. In $\boldsymbol{w}_2$, the rectus femoris, vastus lateralis, and vastus medialis are more activated. In $\boldsymbol{w}_3$, the peroneus longus and gastrocnemius are activated.

Figure 6 shows activated muscles involved in synergies 1–3. Yellow arrows indicate the direction in which muscles move the joint. The first synergy, $\boldsymbol{w}_1$, flexes the hip joint and extends the knee joint with the rectus femoris. It also dorsiflexes the ankle joint with the tibialis anterior. The second synergy,

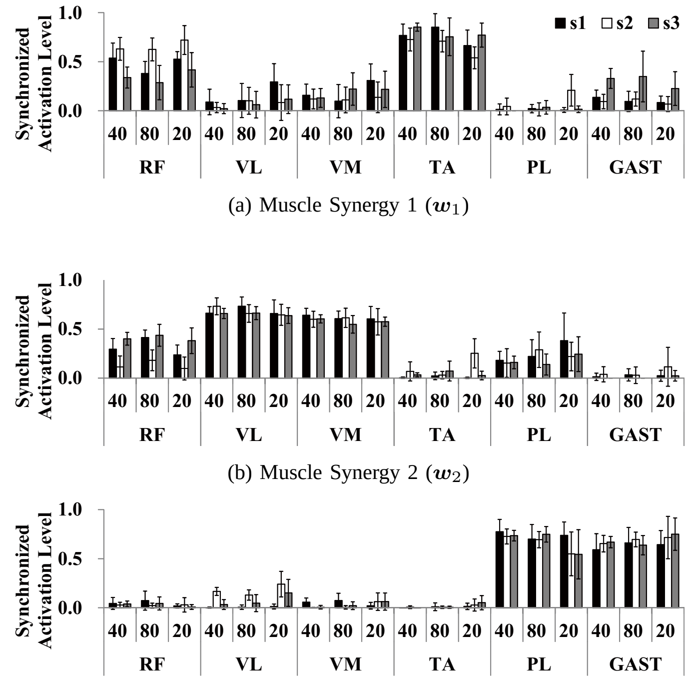


(a) Normal Height - 80 BPM (b) Lower Height - 80 BPM

(c) Normal Height - 40 BPM (d) Loerw Height - 40 BPM

(e) Normal Height - 20 BPM (f) Lower Height - 20 BPM

Fig. 3. Change of Coefficient of Determination.

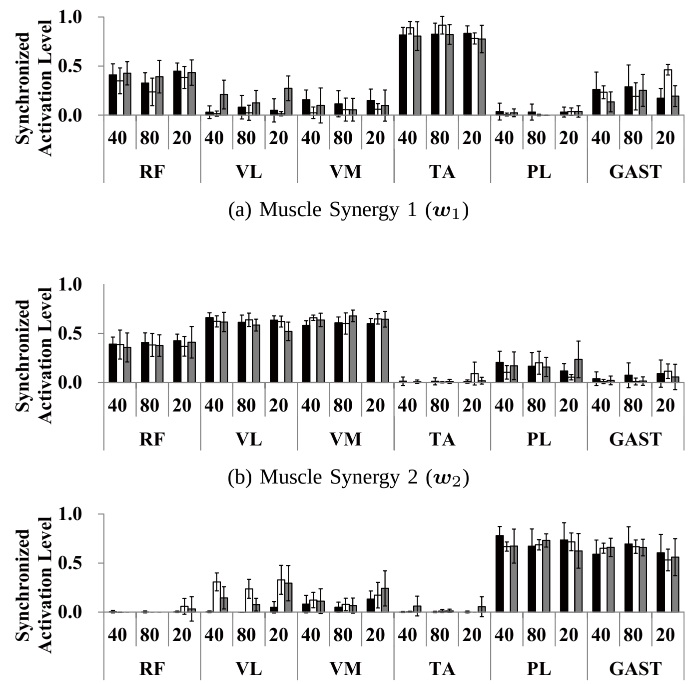


(a) Muscle Synergy 1 ($\boldsymbol{w}_1$)

(b) Muscle Synergy 2 ($\boldsymbol{w}_2$)

(c) Muscle Synergy 3 ($\boldsymbol{w}_3$)

Fig. 4. Extracted Synergies at Normal Height.



(a) Muscle Synergy 1 ($\boldsymbol{w}_1$)

(b) Muscle Synergy 2 ($\boldsymbol{w}_2$)

(c) Muscle Synergy 3 ($\boldsymbol{w}_3$)

Fig. 5. Extracted Muscle Synergies at Lower Height.

$\boldsymbol{w}_2$, flexes the hip joint with rectus femoris, and extends the knee joint with the rectus femoris, vastus medialis, and vastus lateralis. $\boldsymbol{w}_3$ flexes the knee joint with gastrocnemius, and plantarflexes the ankle joint with the gastrocnemius and peroneus longus.

C. Activation Profile

Averages of three activation profiles ($\boldsymbol{c}_1, \boldsymbol{c}_2, \boldsymbol{c}_3$) were computed in every experimental condition. Figure 7 and 8 respectively portray activation profiles for normal and lower heights. In both graphs, (a), (d), and (g) respectively show three activation profiles ($\boldsymbol{c}_1$, $\boldsymbol{c}_2$, and $\boldsymbol{c}_3$) of s1. Similarly (b), (e), and (h) indicate the activation profiles of s2, and (c), (f), (i) illustrate those of s3.

Blue solid lines show activation profiles when subjects stand-up in 40 BPM, red dashed lines show activation profiles in 80 BPM, and green solid lines with green circle markers show activation profiles in 20 BPM. In the graphs, 1 s indicates the time that people raise the hips from a seat.

IV. Discussion

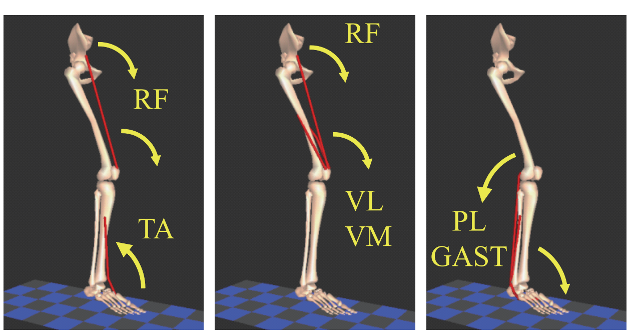
Three muscle synergies ($\boldsymbol{w}_1, \boldsymbol{w}_2, \boldsymbol{w}_3$) were extracted from standing-up motions. Each synergy has similar synchronized activation levels among different experimental conditions: the first synergy $\boldsymbol{w}_1$ mainly activates the rectus femoris and tibialis anterior, the second synergy $\boldsymbol{w}_2$ activates the rectus femoris, vastus lateralis, and vastus medialis, and the third synergy $\boldsymbol{w}_3$ activates the peroneus longus and gastrocnemius. From an anatomical viewpoint, the first synergy dorsiflexes the ankle, extends the knee and flexes the hip, the second synergy flexes the hip and extends the knee, and the third synergy plantarflexes the ankle and flexes the knee. Thinking of the relation between those extracted synergies and the movement of the standing-up motion, the first synergy is thought to pull the ankle and raise the hip up from a seat. Then the second synergy moves the center of mass forward by flexion of the hip and extends the upper body with the knee. Finally, the third synergy stabilizes the posture with antigravity muscles.

In terms of the activation profile ($\boldsymbol{c}_1, \boldsymbol{c}_2, \boldsymbol{c}_3$) corresponding to each synergy, their ordinal structure is clear. In all experimental conditions of the three subjects, firstly the first synergy is activated, then the onset of the second synergy is next, and the third synergy starts at last. However, no clear difference exists on activation profile between normal and lower chair height. That result implies that people use the same synchronized activation and activation profile to adapt to different chair heights. In contrast to the previous study [5], which shows that a lower seat increases joint moment, our result shows little difference in two chair heights. It is because muscle activation is normalized based on the maximum value of each motion. Therefore, joint moment is not considered in this study. Our future direction is to analyze the relation between muscle synergies and joint moment.

The change of speed affects the activation profiles. The slower a person's motion, the longer the activation profiles are. Our results support the idea that people have the same muscle coordination for standing-up motion. Then they actively change the activation profiles of each synergy to achieve the different speeds of the standing-up motion.

From a training viewpoint, it was implied that people need to train three synchronized muscle activations simultaneously. For example, the first synergy requires activation of two muscles (rectus femoris and tibialis anterior) which have different functions such as dorsiflexing ankle and extension of knee and hip. To strengthen $\boldsymbol{w}_1$, it is necessary to train the movement of pulling the ankle and flexing the hip. The next important point for training is the activation profile. People should not merely practice a consistent duration of synergies but the variant period of them to suit various demands.

In our future study, different conditions of standing-up motion will be measured. For example, it will be examined how different stances, such as opened or closed legs, or usage of armrests affects the motion. Additionally, it will be necessary for our synergy model to include more muscles to express the standing-up motion. Although this study examined six muscles, some important inner muscles exist, such as the psoas muscles, which surface EMG barely measures. We use an estimation algorithm to determine even unmeasured muscle activations during the motion to detect synergies that include more synchronized activations.



(a) Synergy1 (b) Synergy2 (c) Synergy3

Fig. 6. Three Extracted Synergies.

V. Conclusion

In this study, synergy analysis was applied to different standing-up motions to elucidate important muscle synergies and their activation profiles. The same set of three muscle synergies was found in the standing-up motions performed with two different chair heights and three different motion speeds. The first synergy works as pulling their feet and raising their hip, the second synergy extends upper body, and the last synergy stabilizes the posture of the whole body. However, the activation profiles corresponding to each synergy differed according to the motion speed. Our study revealed that people have the same muscle synergies. They need only to control their activation profile to achieve the standing-up motion in different chair heights and at different speeds.

Acknowledgments

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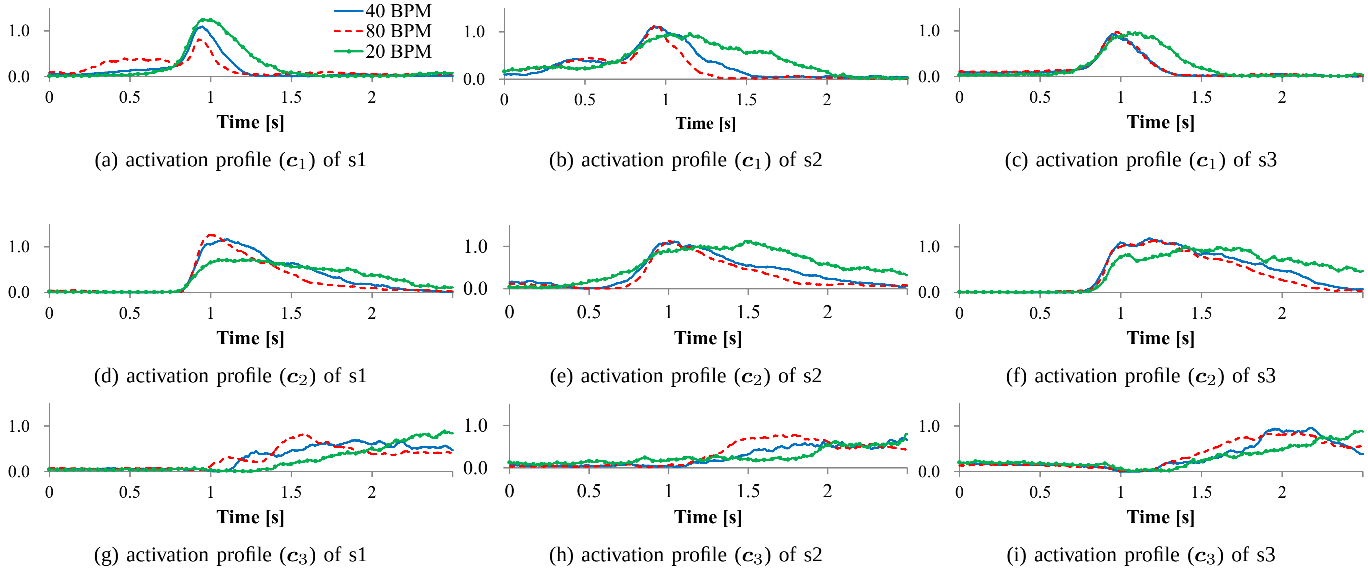
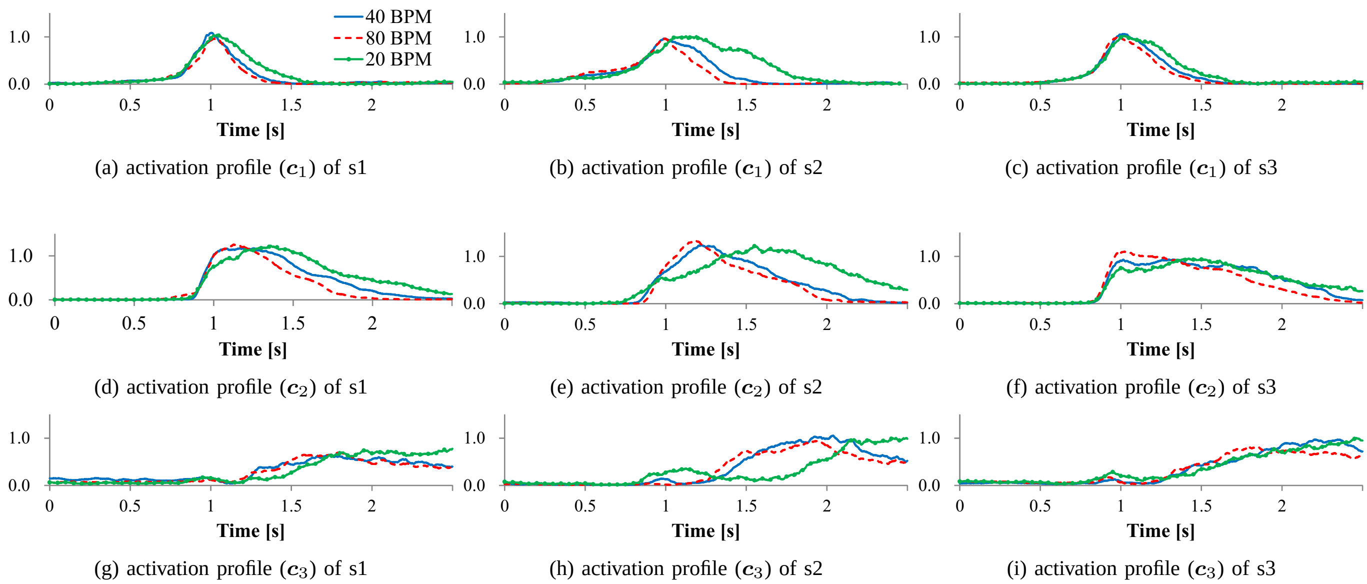


(a) activation profile (c_1) of s1 (b) activation profile (c_1) of s2 (c) activation profile (c_1) of s3

(d) activation profile (c_2) of s1 (e) activation profile (c_2) of s2 (f) activation profile (c_2) of s3

(g) activation profile (c_3) of s1 (h) activation profile (c_3) of s2 (i) activation profile (c_3) of s3

Fig. 7. Activation Profile in Normal Height.



(a) activation profile (c_1) of s1 (b) activation profile (c_1) of s2 (c) activation profile (c_1) of s3

(d) activation profile (c_2) of s1 (e) activation profile (c_2) of s2 (f) activation profile (c_2) of s3

(g) activation profile (c_3) of s1 (h) activation profile (c_3) of s2 (i) activation profile (c_3) of s3

Fig. 8. Activation Profile in Lower Height.