Sit-to-stand motion is an important daily activity, and disability of motion can significantly reduce quality of life. Therefore, it is important to understand the mechanism of sit-to-stand motion in order to prevent such scenarios. The sit-to-stand motion was found to be generated by four muscle groups, through muscle synergy. However, it is unclear how muscle synergy can be controlled. Human sit-to-stand motion may be planned based on body condition before motion. In this study, we aimed to clarify the relationship between body condition and muscle activity during the sit-to-stand motion. Accordingly, we measured the muscle activity when knee movability was disturbed as a condition of body change. We also measured the muscle activity during normal sit-to-stand motion and sit-to-stand motion with disturbed knee movability using surface electromyography. Subsequently, we extracted the muscle synergy from the measured muscle activity and compared the activity levels of muscle synergy. The results revealed that muscle activity contributing to forward bending increased and that contributing to the rise of the hip and stabilization decreased when knee movability was disturbed. These results suggest that humans compensate for disturbed knee movability with forward momentum and bending motion. Moreover, this implies that humans adjust their motion to various environments or body conditions by adjusting the level of forward bending activity.

**Keywords:** sit-to-stand, knee movability, momentum

1. Introduction

Sit-to-stand motion is a crucial activity in daily human life. In other words, disability in sit-to-stand motion significantly impacts the quality of life. Thus, it is important to prevent disability or for rehabilitation after disability to maintain the quality of life.

Rehabilitation of human motion remains challenging owing to physical overwork by therapists resulting in ineffective rehabilitation [1]. To prevent ineffective rehabilitation, human movement mechanisms need to be considered similar to that for gait [2, 3]. For effective disability prevention or rehabilitation based on human movement mechanisms, it is imperative to comprehend the mechanism of the sit-to-stand motion.

A redundancy problem is encountered when attempting to understand the human movement mechanism, because humans have more muscles than joints. Thus, the muscle synergy hypothesis was proposed to solve the redundancy problem [4]. According to this hypothesis, humans do not control each muscle independently; instead, they control groups of several muscles. These muscle groups are known as muscle synergies. Based on this hypothesis, the sit-to-stand motion in humans is generated by four muscle synergies [5]; further, humans change their motion by adjusting the amplitude or activation timing of muscle synergy [6]. Moreover, we clarified that the muscle synergies of sit-to-stand motion are altered by disturbances in the visual or vestibular input [7].

However, the mechanism for adjusting to various environments should also be considered when attempting to understand the mechanism of sit-to-stand motion. When adjusting to various environments, humans should adjust their muscle activity based on their body condition. During stabilized standing, humans use various strategies to stabilize their posture upon various disturbances [8]. Therefore, to understand mechanism of sit-to-stand motion, it is important to understand the relationship between body condition and muscle activity. The present study aims to clarify how humans adjust their muscle activity during sit-to-stand motion when body condition is changed.

In this study, we focused on knee movability when the body condition changed, primarily because smooth knee joint movement is an important factor in performing the sit-to-stand motion easily. Therefore, the primary objective of this study was to understand how humans adjust their muscle activity during the sit-to-stand motion when knee movability is disturbed.
2. Method

As the range of motion of the knee joint is the largest in the sit-to-stand motion, it is significantly affected depending on whether the knee joint can be moved smoothly. Therefore, understanding how humans change their muscle activity when the knee joint cannot move smoothly can help clarify adjustment of muscle activity to adapt to altered body conditions. In the present study, we focused on knee joint movability to clarify how humans change their muscle activity under altered body conditions when knee joint movability is disturbed.

As muscle activity changes when knee joint movability is disturbed, we hypothesized two types of adaptation. First, humans can increase the muscle activity contributing knee movement to recreate the same motion as that before knee movement is disturbed. Second, humans can generate a new motion to adapt to the body condition in which knee joint movability is disturbed. In this study, we clarified how humans change the method of muscle activation to adapt to body conditions when knee joint movability is disturbed.

We compared sit-to-stand movements with normal and disturbed knee movability to clarify the strategy for adapting to the body condition when the movability of the knee joint is disturbed. We also compared sit-to-stand motion with disturbed knee movability and that after knee movability returned to normal. The aim of this comparison is to determine whether the new strategy used for adapting to disturbed knee movability remained after knee movability had returned to its original condition. As hypothesized, humans can increase activation of muscles that contribute to knee movement for recreating the same movement as that before the disturbance of knee movement. Therefore, in this comparison, we focused on the activation level of muscle activity. As humans utilize the synchronization of several muscles that contribute to knee movement to recreate the same movement before knee movement is disturbed, we compared the activation level using muscle synergy. More specifically, as we hypothesized that humans can activate muscle synergies that contribute to raising the hip and extending the body further because knee muscles are activated in the synergies, we focused on the activation level of muscle synergies. We aimed to find a new strategy for muscle activation to adapt to the new body condition in which the movability of the knee joint is disturbed, as stated above.

In this study, we disturbed knee joint movability using the equipment shown in Fig. 1. Muscle activity was measured to clarify the change in muscle activity during the sit-to-stand motion when knee movability was disturbed. As the equipment was applied to both the right and left sides of the body, the effect of the equipment on movement was assumed to be symmetrical. Therefore, we measured the activity of the muscles on the right side of the participants to investigate the effect of the equipment. The measured muscles included the extensors and flexors of the ankle, knee, hip, lumbar, and neck joints. If the human body is represented by a six-link model that contains the head, torso, lumbar region, thigh, shank, and foot, muscle activity involved in sit-to-stand motion could be measured based on the activity of these muscles [7]. Additionally, the start and end of the sit-to-stand motion should be defined to clarify the change in muscle activity between different conditions. The kinematics of the motion were used to define the start and end times of the sit-to-stand motion. The detailed procedures for measuring for activity, motion kinematics, and reaction force are described in our previous study [9].

3. Experiment

3.1. Measurement Experiments

The experiment was conducted in four male participants aged 20–30 years. Each participant performed a sit-to-stand motion in the environment shown in Fig. 1.

First, a normal sit-to-stand motion was performed 30 times without any disturbance. Next, the participants wore equipment (teaching kit for simulating the elderly, Sanwa Manufacturing Co., Ltd.) to disturb knee movability, and sit-to-stand motion was again measured 30 times. The equipment disturbed knee flexion and extension with viscous resistance, and flexion with elastic resistance, which made it difficult to flex the knee joint over 90°. Finally, the equipment was removed and the sit-to-stand motion was again measured 30 times. In each condition, the participant rested once every 10 or 15 times; however, the rest time varied according to the conditions of the participant or measurement device. Participants were asked to place their arms on their chest and not to use their arms when they performed the sit-to-stand motion, to eliminate the effects of arm movement. The participants were also instructed to perform the sit-to-stand motion at a comfort-
able speed. The height of the chair was adjusted such that the thigh remained horizontal, and the foot position was adjusted such that the sit-to-stand motion could be performed comfortably. The participants were informed that knee movability would be disturbed using the equipment before the experiment.

Muscle activity, motion kinematics, and reaction force on the feet and hip were measured using a surface electromyogram (MiniWaveInfinity, Cometa) at 2 kHz, an optical motion capture system (MAC3D, MotionAnalysis) at 100 Hz, and a force plate (TF4060 for feet and TF3040 for the hip, Tec Gihan Co., Ltd.) at 2 kHz, respectively.

The measured muscles were the same as described in our previous study [7]: trapezius (TRP), rectus abdominis (RA), erector spinae (ES), external oblique (EO), gluteus maximus (GMX), gluteus medius (GMD), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), biceps femoris long head (BFL), semitendinosus (SEM), tibialis anterior (TA), gastrocnemius medialis (GAM), gastrocnemius lateralis (GAL), peroneus (PER), and soleus (SOL). As the sit-to-stand motion is symmetric, we measured only the right side. Approval of ethical and experimental procedures and protocols was granted by the Institute Review Board of The University of Tokyo.

3.2. Analysis

3.2.1. Extraction of Muscle Synergy

Muscle synergy was extracted from the measured muscle activity. First, we applied a bandpass filter between 20 Hz to 500 Hz to remove noise. The filter was built using a fourth-order Butterworth filter to measure the signal from the surface electromyogram. Second, we rectified the data and applied a low-pass filter with a cut-off frequency of 5.3 Hz to extract muscle activity [10]. This filter was constructed using a second-order Butterworth filter. Third, we normalized the data based on the maximum value of each muscle in each participant. Finally, we extracted the muscle synergy from the normalized data using non-negative matrix factorization [11].

3.2.2. Comparison of Spatial Patterns

We compared muscle synergy among the experimental conditions. Spatial patterns are considered to be coded in the spinal cord [12], and previous research has shown that spatial patterns do not vary among conditions [6, 7]. We hypothesized that the spatial pattern would not change in this experiment as well. To validate this, we calculated the similarity of spatial patterns using the same equation as in our previous study [7] and determined whether the similarity was greater than 0.4 [13]. First, we calculated the average spatial pattern for each condition of each participant. We then calculated the average activity of each muscle in the spatial pattern to calculate the average spatial pattern. Second, we calculated the correlation coefficient of the averaged spatial pattern between the normal and knee-supported conditions and between the normal and after-conditions for each participant. Finally, we calculated the mean and 95% confidence intervals of the four participants and checked whether the lower confidence was higher than 0.4.

3.2.3. Comparison of Temporal Patterns

In this study, we compared the temporal patterns of muscle synergy. We hypothesized that the participants would activate their knee muscles more in the knee-disturbed conditions than in the normal condition, primarily because knee movability is disturbed by the knee supporter. Therefore, we hypothesized that muscle synergy contributing to knee movement would increase. To validate this hypothesis, we compared the peak value of the temporal pattern of muscle synergy. First, we calculated the maximum value of the temporal pattern for each muscle synergy in each trial. Second, we compared the maximum value of the temporal pattern of each muscle synergy among the trials by employing an analysis of variance and a post-hoc test [14].

Furthermore, we compared the activation period of muscle synergy. We thus hypothesized that muscle synergy contributing to knee movement would be prolonged because knee movement is disturbed. Therefore, we compared the activation period of muscle synergy to validate this hypothesis. We defined the activation period as the time when the activity of the muscle synergy temporal pattern was greater than half of the maximum activity in each trial. Instead of using a constant threshold value, the threshold value was set according to the maximum value indicated by muscle activity, thus allowing the calculation of activity time independent of the increase or decrease in muscle activity [15]. Moreover, we also considered the difference in activating period among participants, primarily because the speed of motion was varied among participants. Therefore, we normalized the period based on the average activating period of each muscle synergy under normal conditions. In other words, we compared the activation periods using the ratio to the activating period under normal conditions. Subsequently, we compared the normalized period with the analysis of variance and post-hoc test [14].

4. Results

4.1. Results of Muscle Synergy

Figure 2 illustrates the muscle synergy extracted of the measured data from one participant. We extracted the muscle synergy in each trial for each participant and averaged the muscle synergy in each condition, as shown in Fig. 2. Accordingly, the top side indicates the spatial pattern and the bottom side illustrates the temporal pattern. From the left to right, the graphs show synergy 1 (forward bending), synergy 2 (hip raising), synergy 3 (extension), and synergy 4 (stabilization). In the spatial pattern, the horizontal axis shows muscles and the vertical axis shows activity, whereas in the temporal pattern, the horizontal axis refers to time and the vertical axis corresponds to activity. In the spatial patterns, white bars, white bars with
horizontal lines, and black bars shown relative muscle activity in normal, disturbed, and after conditions. In the graph of temporal patterns, the black solid, black dotted, and gray dashed lines show normal, disturbed knee, and after conditions, respectively.

In the extracted muscle synergy, synergy 1 was found to activate the lumbar flexor rectus femoris (RA) and external oblique (EO) to bend the upper body forward, while synergy 2 activates the ankle dorsiflexor tibialis anterior (TA) and knee extensor rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) to move the body forward and raise the hip; synergy 3 activates the hip extensor gluteus maximus (GMX) and gluteus medius (GMD) and the knee extensor vastus lateralis (VL) and vastus medialis (VM) to extend the entire body; finally, synergy 4 activates the ankle plantarflexor gastrocnemius lateralis (GAL), gastrocnemius medialis (GAM), peroneus (PER), and soleus (SOL) to pull the body backward and stabilize. These synergies are compatible with those shown in previous studies [5–7].

4.2. Results of Reaction Force

Figures 3–5 illustrate the data from the force plate. Fig. 3 shows the foot reaction force, Fig. 4 shows the hip reaction force, and Fig. 5 shows the position of the center of pressure of the foot. The data in these figures were averaged in each condition for each participant. In Figs. 3 and 4, the left top graph shows the time variance of the upward force, and the right top graph shows the time variance of the forward force. In the right bottom graph, the horizontal axis corresponds to the force in the forward direction, the vertical axis corresponds to the force in the upward direction.

In Fig. 5, the left and right top graphs show time variance of center of pressure position in the forward and leftward directions, respectively. In the bottom right graph, horizontal and vertical axes show center of pressure in forward and leftward directions, respectively. In each graph, the black solid line shows the normal condition, the black dotted line shows the disturbed knee condition, and the gray dashed line shows the after condition.

4.3. Comparison Between Conditions

Using the obtained data, we compared the spatial and temporal pattern of muscle synergy.

4.3.1. Comparison of Spatial Patterns

First, we compared the spatial patterns. Fig. 6 illustrates the averaged spatial pattern of each condition from all trials involving all participants. From the top to bottom in the figure, the graph shows the averaged spatial pattern of synergy 1 (forward bending), synergy 2 (hip...
Analysis of Muscle Activity of Sit-to-Stand Motion

Fig. 4. Example of hip reaction force. The graph shows the averaged data in each condition from one participant. The left and right top graphs show the time variance of upward and forward force, respectively. The right bottom graph, the horizontal axis corresponds to the force in forward direction and the vertical axis corresponds to the force in the upward direction. The black solid, black dotted, and gray dashed lines show the normal, knee disturbed, and after conditions.

Fig. 5. Example of center of pressure. The graph illustrates averaged data in each condition from one participant. The left and right top graphs show the time variance of forward position and leftward position, respectively. In the bottom right graph, the horizontal and vertical axes correspond to the position in forward and leftward directions. The black solid, black dotted, and gray dashed lines show the normal, knee disturbed, and after conditions.

4.3.2. Comparison of Peak Values of Temporal Patterns

We compared the peak values of the temporal patterns. Fig. 7 shows the calculated average peak values. In the figure, from the left to right, the graph shows the averaged peak value of the temporal patterns of synergy 1 (forward bending), synergy 2 (hip raising), synergy 3 (extension), and synergy 4 (stabilization). In the graph, the horizontal axis illustrates the conditions and the vertical axis corresponds to the peak value. Error bars indicate the standard deviation, and upper and lower limits of the 95% confidence intervals for the similarity in spatial patterns. (A) shows the similarity between the normal and disturbed knee conditions, and (B) shows the similarity between the normal and after conditions. As all similarities are higher than 0.4, similar spatial patterns were considered to be used in all synergies between the normal and disturbed knee and between the normal and after conditions.

Table 1 lists the similarities calculated using the correlation coefficients.

The table shows the average, standard deviation, as well as the upper and lower limits of the 95% confidence intervals of the calculated correlation coefficient. From the top to bottom, the table shows synergies 1, 2, 3, and 4, and from the left to right, it shows the average, standard deviation, and upper and lower limits of the 95% confidence intervals for the similarity in spatial patterns. (A) shows the similarity between the normal and disturbed knee conditions, and (B) shows the similarity between the normal and after conditions. As all similarities are higher than 0.4, similar spatial patterns were considered to be used in all synergies between the normal and disturbed knee and between the normal and after conditions.
Table 1. Similarity in spatial patterns.

<table>
<thead>
<tr>
<th></th>
<th>Average ± standard deviation</th>
<th>Upper 95% confidence</th>
<th>Lower 95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Between normal and disturbed knee</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Synergy 1</td>
<td>0.84±0.16</td>
<td>1.1</td>
<td>0.58</td>
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<tr>
<td>Synergy 2</td>
<td>0.93±0.02</td>
<td>0.97</td>
<td>0.89</td>
</tr>
<tr>
<td>Synergy 3</td>
<td>0.88±0.03</td>
<td>0.93</td>
<td>0.83</td>
</tr>
<tr>
<td>Synergy 4</td>
<td>0.94±0.05</td>
<td>1.03</td>
<td>0.86</td>
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<td>(B) Between normal and after</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Synergy 1</td>
<td>0.98±0.02</td>
<td>1.01</td>
<td>0.95</td>
</tr>
<tr>
<td>Synergy 2</td>
<td>0.97±0.01</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>Synergy 3</td>
<td>0.94±0.04</td>
<td>1.01</td>
<td>0.88</td>
</tr>
<tr>
<td>Synergy 4</td>
<td>0.97±0.03</td>
<td>1.01</td>
<td>0.92</td>
</tr>
<tr>
<td>(C) Between disturbed knee and after</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synergy 1</td>
<td>0.87±0.15</td>
<td>1.10</td>
<td>0.63</td>
</tr>
<tr>
<td>Synergy 2</td>
<td>0.91±0.05</td>
<td>1.00</td>
<td>0.83</td>
</tr>
<tr>
<td>Synergy 3</td>
<td>0.86±0.07</td>
<td>0.97</td>
<td>0.75</td>
</tr>
<tr>
<td>Synergy 4</td>
<td>0.94±0.10</td>
<td>1.09</td>
<td>0.79</td>
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Fig. 7. Averaged peak value of temporal patterns. From the top to bottom, the graph illustrates the average and standard deviation of peak values in synergy 1 (forward bending), synergy 2 (hip raising), synergy 3 (extension), and synergy 4 (stabilization).

Fig. 8. Activation period of muscle synergy. These graphs illustrate the normalized activation period of the temporal pattern of muscle synergy. From the top to bottom, the graph illustrates the average and standard deviation of activation period of synergy 1 (forward bending), synergy 2 (hip raising), synergy 3 (extension), and synergy 4 (stabilization).

deviation. Accordingly, we compared this peak value using an analysis of variance (ANOVA) and post-hoc tests. ANOVA revealed significant differences between experimental conditions for synergies 1, 2, and 4 ($p < 0.001$). Consequently, significant differences were found between the following conditions:

- The activity of synergy 1 (forward bending) was larger in the knee disturbed condition than in the normal condition ($p < 0.001$) and the after condition ($p < 0.001$).
- The activity of synergy 2 (hip raising) was smaller in the knee disturbed condition than in the normal condition ($p < 0.001$).

4.3.3. Comparison of Activation Period of Temporal Patterns

We compared the activation periods of the temporal patterns of muscle synergy. Fig. 8 shows the average and standard deviation of the calculated normalized activation period. Accordingly, the figure shows the normalized activation period of the temporal pattern of the muscle synergy. From the left to right, the graph shows

- The activity of synergy 4 (stabilization) was smaller in the knee disturbed condition than in the normal condition ($p < 0.001$) and the after condition ($p < 0.001$).
synergy 1 (forward bending), synergy 2 (hip raising), synergy 3 (extension), and synergy 4 (stabilization). The horizontal axis corresponds to the conditions, and the vertical axis corresponds to the activation period. Error bars indicate standard deviation. As the data were normalized based on the average under normal conditions, the activation period under normal conditions for all the synergies was 1.0. Moreover, we compared this activation period using analysis of variance (ANOVA) and post-hoc tests. ANOVA revealed significant differences between experimental conditions for synergy 1 ($p = 0.002$) and synergy 3 ($p = 0.003$). The results of the post-hoc test showed that synergy 1 (forward bending) was activated significantly longer in the normal condition than in the knee disturbed condition ($p = 0.001$). Moreover, synergy 3 (extension) was significantly longer in the knee-disturbed condition than in the after-condition ($p = 0.003$). Meanwhile, no significant differences were found between the normal and after-conditions.

5. Discussion

In this study, we investigated the change in the sit-to-stand motion when there was a change in the body because the knee supporter disturbs knee movement. This revealed that the activity of muscle synergy contributing to forward bending increased and the activity of muscle synergy contributing to hip raising and stabilization decreased. This result can be explained as follows. The larger activity of muscle synergy contributing to forward bending can be attributed to compensation for knee movement disturbance with the momentum of the upper body. Additionally, because participants compensate for knee movement disturbance with movement of the hip or lumbar joint because other joints, such as hip or lumbar joints, were not disturbed even though the knee joint was disturbed. Therefore, the activity of muscle synergy 1, which is responsible for bending the body forward for flexing the hip or lumbar joint, was increased. The lower activity of muscle synergy 2 contributing to raising hip may be attributed to the action of raising the hip, which can be performed with a smaller power using the momentum of the body bent forward. In other words, as it was difficult to generate sufficient power to raise the hip because of knee movement disturbance, the muscle synergy contributing to forward bending increased. The lower activity of muscle synergy 4 contributing to stabilization may be because stabilization, which pulls the body backward, can be achieved with a smaller power, as the activity of raising the hip to push the body forward is decreased. Another possible cause of decreased activity in muscle synergy 4 is the effect of knee disturbance. Owing to the additional equipment on the knee joint that disturbs knee flexion, the participants may not have to keep activating muscles to keep extending their knee joint, which may result in decreased activity of muscle synergy 4.

Furthermore, comparing the activation periods of muscle synergy revealed that the activation period of muscle synergy contributing to bending the body forward was decreased. This also implies that participants compensate for knee movement disturbance with the momentum of bending the body forward. More specifically, participants bend their body forward more in a shorter duration as the participants tend to compensate for knee movement disturbance with the momentum of bending the body forward.

As mentioned above, knee movement disturbance may primarily affect the activation of muscle synergy 1, contributing to bending the body forward. In other words, disturbance to knee movement alters the sit-to-stand movement program by increasing the activity of synergy 1. Notably, people utilize other body parts, such as the upper trunk, to compensate for change in the body. Knee extension is an essential motion for completing the sit-to-stand motion, and restoration of extension is important in rehabilitation [16]. If the body bending motion reflects adjustment of the motion program caused by disturbed knee extension, it is crucial to improve the body bending motion for rehabilitation of the sit-to-stand motion. In future studies, it will be necessary to validate whether people change their bending motion to adjust for different body changes or environmental changes, such as chair height. However, as this experiment was conducted with only four participants, the results should be validated in more participants. Another limitation of this study is that only the movement of the knee joint was disturbed. It would be interesting to investigate how altered body conditions other than the knee joint affect muscle synergies in more participants.

6. Conclusion

In this study, we aimed to clarify the change in muscle activity associated with the sit-to-stand motion when knee movement was disturbed. Consequently, when knee movement was disturbed, the activity of muscle synergy contributing to bending the body forward increased, and activity of the muscle synergy contributing to raising the hip and stabilization decreased. This result implies that humans compensate for knee movement disturbance with the momentum of bending the body forward. It also implies that the changes in the motion program for the sit-to-stand to deal with changes in the body or environment is associated with changes in the activity of bending the body forward. This should be validated by investigating other body or environmental changes.

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