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# Lower-limb moments during sit-to-stand movement with different handrail grip position and trunk tilt angle

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*Abstract*— **Reducing the burden on the lower-limb joint can improve the quality of life for individuals who encounter difficulties in sit-to-stand movement due to weak lower limbs. This research compared several conditions in which the handrail grip position and the trunk-tilt angle differed in terms of the moments of the lower-limb joint. It was determined that the maximum reduction of hip moment occurred when the participants stood up from an erect sitting posture with the grip position above the great trochanter. The maximum reduction of knee moment was observed when the participants stood up at a tilt angle of 30° with the grip position above the great trochanter. In contrast, the participants preferred another condition whereby the upper body was tilted 30° and the handrail grip position was located beneath the chest. Moreover, two types of strategies for handrail use were observed among the participants. In one strategy, the handrail is primarily used when the gluteal region separates from the chair's surface. In another strategy, the handrail is used during the entire STS movement. These results aid in the determination of the optimal conditions required for handrail use.**

## I. INTRODUCTION

Sit-to-stand (STS) movements are an important daily activity in addition to walking and stair-climbing. In recent years, with the aging of the general population, there has been an increase in the number of individuals who encounter difficulties in performing STS movement due to hypokinesia or knee diseases. There is a deterioration in the quality of life if these movements cannot be easily performed or if pain is experienced during motion. Hence, the investigation of the burden on lower-limb joints during STS movement can potentially contribute to the development of a supportive environment for affected individuals.

To date, numerous studies have been conducted to investigate the moments of lower-limb joints during STS movements [1]. Rodosky et al. and Burdett et al. investigated the moments of lower-limb joints during STS movement for chairs of different heights [2], [3]. They determined that a higher chair could result in lower joint moments. Fleckenstein et al. investigated the relationship between the initial angle of the knee joint to the moment of the hip joint. It was determined that the maximum hip joint moment was larger when the initial knee flexion angle was 75°, compared to the initial knee angle of 105° [4]. Gillette et al. investigated how the position of the feet influenced the moments of the lower-limb joints [5]. Ankle and knee moments significantly increased when a foot was positioned in the posterior position compared to the anterior position. Schenkman et al. discovered that the momentum generated by the forward flexion of the upper body prior to seat-off was transmitted to the lower limbs in the next phase [6]. Those suffering from knee OA do not take advantage of such upper body momentum [7]. Doorenbosch et al. performed an experiment whereby participants in an erect sitting positioned flexed their upper body forward as far as possible and then stood up. This resulted in a smaller knee moment when compared to the normal STS movement [8]. Shepherd et al. concentrated on the initial tilt angle of the upper body and they determined that with the increase of the initial tilt angle of the upper body, the duration of maximum support moment increased [9]. Based on the aforementioned results, standing up from higher chairs, increasing the initial knee flexion angle, placing the feet at an appropriate position and exploiting the flexion of the trunk are all able to reduce the burden of lower-limb joints during the STS movement. These studies investigated STS movement without handrails or other assistive tools.

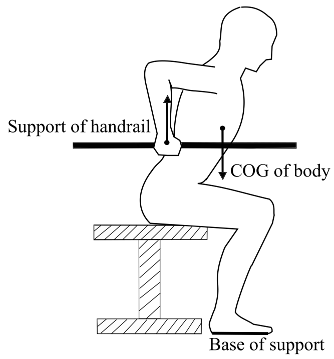


Fig. 1. Grip position, center of gravity (COG) of body and base of support

Handrails are widely used to reduce the burden on the lower limbs. For example, Kinoshita et al. investigated the optimum height, shape, and position of handrails [10], [11]. They determined that the use of low handrails led to an increase in the maximum flexion angle of the hip joint, knee joint, as well as the trunk, and a combination of low and high handrails resulted in the largest decrease of the lower-limb joint moments. Takeda et al. compared four types of handrails in a study that included pregnant women [12]. In the case of bilateral handrails, the participants tended to apply additional weight and symmetric lower-limb joint moments were observed during the experiments. Moreover,

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a discussion on the determination of the better side to set a handrail assuming a patient suffers from unilateral knee osteoarthritis was presented [13], [14]. It was determined that a larger decrease of the maximum knee moment and greater stability with a handrail set at the impaired side. O'Meara et al. investigated the effects of a unilateral handrail during STS movement and a larger knee moment was observed at the side with the handrail, while the knee moment of the other side became smaller [15]. These studies focused on the height, shape and lateral position of handrails. Some of the earlier reports are in disagreement with each other, resulting in continuing debates and discussions. Katsuhira et al. investigated the effects of different grip positions on a handrail during natural STS movement and found that the position above the great trochanter resulted in the smallest knee and hip moments [16]. According to these studies, it is evident that handrails can reduce the burden on lower-limb joints during STS movement. However, there are many associated parameters that should be considered. To date, there is no general consensus on the effective utilization of handrails.

Based on previous studies on STS movement with or without handrails, it has been determined that grip position on the handrail and the trunk-tilt angle both significantly influence the lower-limb joint moments. However, there are few studies in which the grip position and trunk tilt angle are simultaneously controlled. This research compares several conditions whereby the grip position on the handrail and trunk tilt-angle differ. The objective is to specify STS movements that minimize the burden on the lower limbs. From a mechanical perspective, as shown in Fig. 1, the total moment of the lower-limb joints decreases if the center of gravity (COG) of the body and the grip position are horizontally close to the base of support. In comparison, the hip joint moment decreases if the COG and the grip position are close to the hip joint. Moreover, healthy and young individuals can rapidly tilt their trunks forward and exploit the reactive moment around their hips to stand up using smaller muscular contractions of their lower bodies [6]; however, the present report does not address such dynamic STS movement.

## II. METHODS

### A. Participants

Five healthy male (25 ± 6.2-year old, 174.6 ± 1.7 cm, 59.2 ± 2.2 kg) participated in the experiment. None of the participants had a history of diseases that affected STS movement and they were informed of the significance and objective of the investigation prior to the experiment.

### B. Settings

As shown in Fig. 2, a height-adjustable chair was used in this experiment and its height was adjusted to be the same height as that of each participant's knee. One handrail was set at each side of the chair with a separation distance of 0.7 m. They were adjusted to the height of the greater trochanter when the participants were in a standing posture.

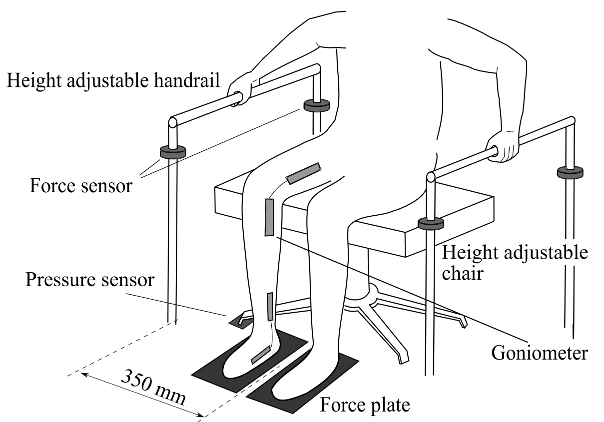



Fig. 2. Settings of STS experiment

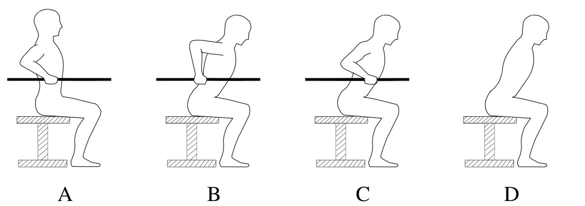



Fig. 3. Schematic showing the four conditions used in the experiment

The force applied to the handrails was measured using internal force sensors (PFS055YA251G6, Leptrino, Japan), while the ground reaction force was measured using a force plate positioned under each foot. This plate consisted of four load cells (FX1901, TE Connectivity, USA). The angles of the ankle and knee joints of each lower limb were measured using two goniometers (SG series, Biometrics Ltd., UK). A pressure sensor (FSR-406, Interlink Electronics, USA) was positioned under the chair to determine the instance of seat-off. Prior to standing up, the participants were instructed to adjust their knee joints at a flexion of 90° and the distance between their feet was set as the same distance as that between their acromion. In addition, they were not allowed to move their feet during the trials. Moreover, to control the posture of their head, a mark was set at a height of 1.7 m and at a distance of 3 m in front of the chair. Participants were instructed to look at the mark all the time during the STS movement.

### C. Tasks

Every participant performed STS movement under four conditions. As shown in Fig. 3, in condition A, the grip position was above the greater trochanter and participants stood up from an erect sitting position. Under this condition, the grip position and the COG of the upper body were extremely close to the hip joint. Condition B also required participants to grip the position above the greater trochanter, but with a trunk-tilt angle of 30°. Under this condition, the grip position was near the hip joint while the COG of the body was within the base of support. For condition C, the grip position was above the ankle joint and the trunk-tilt angle was 30°. The grip position and the COG of the body were both within the base of support under this condition. For the control group, condition D required the participants to stand up from the initial tilt angle of 30°, similar to condition B and C. However, their arms were folded across their chest in this case. Under all the conditions, the participants were instructed to not flex their trunk any further until they left their seats. The trunk-tilt angle was aligned with reference marks on the wall beside the participant. Also, the initial trunk-tilt angle was monitiored by an experimenter for each trial. The speed of the movement and the force applied to the handrails were determined by the participants provided that they could perform these tasks naturally. Moreover, the four conditions were implemented in random order and the STS movement was repeated eight times for each condition. Hence, a total of 32 trials were performed by each participant. At the end of the experiment, all the participants were questioned to determine the most comfortable condition among the aforementioned four.

*D. Data Analysis*

The experimental data were obtained at a sampling rate of 50 Hz. The data during the period of the seat-off to the instance when the knee joint was at a flexion of 10° were normalized to 100% of the task and analyzed. The static joint moments of ankle, knee and hip during the movement were calculated in this study provided that the effects of inertia were relatively small. The force applied to the handrails differed for each individual, and thus it was difficult to compare the results for all the participants. Therefore, the effective weight was determined by subtracting the component of the weight supported by the handrails from the actual weight of the participants. Thus, the joint moments were normalized by the height and effective weight of each participant as follow:

$$W_{eff} = W - \frac{F_r}{g} \tag{1}$$

$$M_{jnorm} = \frac{M_j}{W_{eff} \times H} \tag{2}$$

where $W_{eff}$ represents the effective weight, $W$ represents the actual weight, $F_r$ is the handrail reaction force, $M_{jnorm}$ is the normalized joint moment, $M_j$ represents the actual internal joint moment, $H$ represents the height of participants, and $g$ is the acceleration due to gravity.

## III. RESULTS

The internal joint moments of one participant are shown in Fig. 4 as a representative result. Under all conditions, the maximum of the lower-limb joint moments was observed immediately after leaving the seat. For the knee moment, condition B was the smallest for nearly all the cycle. Regarding the hip moment, condition A was the smallest, while condition B was the largest. These results were calculated as the mean of all the trials for one participant.

The mean values of the maximum lower-limb joint moments of all participants are shown in Fig. 5, as well as the standard errors among the participants. Using two-way

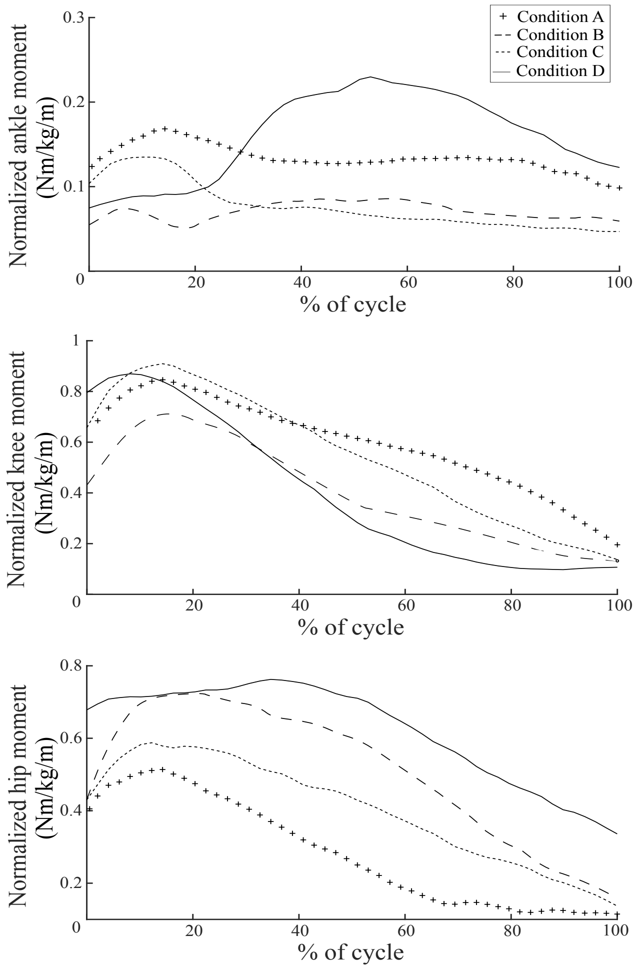



Fig. 4. Representative ankle joint moment, knee joint moment, and hip joint moment

ANOVA in which the factors were the participants and the conditions of the STS movement, significant differences were observed among the conditions for all the joints. Therefore, as a post hoc analysis, we compared the joint moments for two of the three conditions using two-way ANOVA for each joint.

The conditions of the STS movement significantly influenced the maximum knee moment among the three conditions ($F(2, 105) = 29.9, p < 0.001$; interaction $p < 0.001$). The maximum knee moment for condition B was the smallest among the three conditions (B vs. A: $F(1, 70) = 43.2, p < 0.001$; B vs. C: $F(1, 70) = 44.1, p < 0.001$). However, there was no statistically significant difference between conditions A and C ($F(1, 70) = 0.05, p = 0.83$). Moreover, considering the interaction effects, no statistically significant difference was observed between conditions B and C for two participants, and among three conditions for another participant.

The effects on the maximum hip moment were also determined to be statistically significant ($F(2, 105) = 28.6, p < 0.001$; interaction $p < 0.001$). The largest reduction was observed for the maximum hip moment under condition

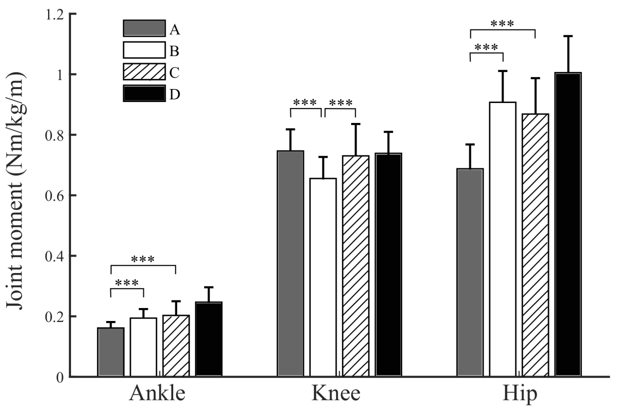



Fig. 5. Maximum joint moments under the four different conditions. The mean and standard errors among the participants. Two-way ANOVA was used to test for the effects of conditions and participants. Asterisks *** indicate a significance level of 0.001.

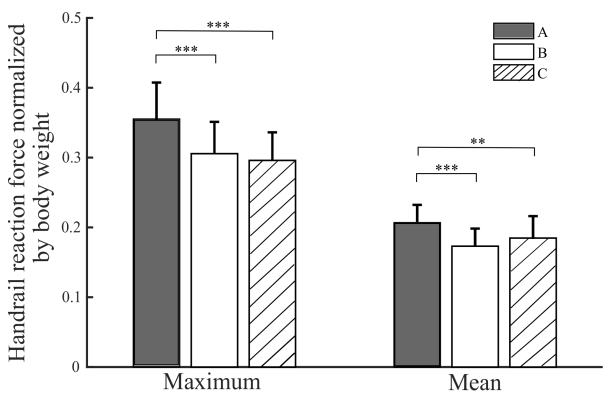



Fig. 6. The maximum and mean handrail reaction force under three different conditions. The mean and standard errors among the participants. Two-way ANOVA was used to test for the effects of conditions and participants. Asterisks ** and *** indicate the significance level of 0.01 and 0.001, respectively.

A (A vs. B: $F(1,70) = 54.2, p < 0.001$; A vs. C: $F(1,70) = 32.4, p < 0.001$). However, the effects did not seem to be statistically significant for conditions B and C ($F(1,70) = 1.9, p = 0.17$). For the interaction effects, no significant difference was observed between conditions A and C for one participant, and among all three conditions for another participant.

The conditions significantly influenced the maximum of the ankle moment as well ($F(2,105) = 11.5, p < 0.001$; interaction $p < 0.05$). The maximum for condition A was the smallest (A vs. B: $F(1,70) = 15.2, p < 0.001$; A vs. C: $F(1,70) = 22.8, p < 0.001$) and there was no statistically significant difference between condition B and C ($F(1,70) = 0.9, p = 0.36$). However, regarding the results for each participant, for two individuals, the maximum ankle moment was the largest under condition A. Hence, a definite conclusion cannot be made with regards to the effects of the conditions on the ankle moments.

On average, condition B yielded the smallest knee moments, followed by condition A and C. Condition A resulted in the smallest hip moments, followed by condition B and C.

During the entire STS movement, the direction of the handrail reaction force was almost upward and the horizontal component was extremely small. The maximum and mean values of the handrail reaction forces under the three conditions during the STS movement are shown in Fig. 6. In this case, the handrail reaction force was the sum of two handrails. The participants tended to apply larger forces to the handrails under condition A in terms of the maximum (A vs. B: $F(1,70) = 29.9, p < 0.001$; A vs. C: $F(1,70) = 121.2, p < 0.001$) and mean (A vs. B: $F(1,70) = 12.0, p < 0.001$; A vs. C: $F(1,70) = 9.9, p < 0.01$). No statistically significant difference was observed between condition B and condition C.

The handrail reaction force of the five participants can be largely divided into two patterns as shown in Fig. 7. For type 1 (2 individuals), during almost the entire cycle the force applied to the handrails was the largest under condition A, while the smallest under condition C. Moreover, considering condition A and B, the value at 0% of the cycle was relatively small compared to type 2. It decreased by approximately 1/5 at 50% of the cycle but did not decrease to zero at 100% of the cycle. In contrast, the feature of type 2 (3 individuals) was that a large force was applied to the handrails at the instance of seat-off and the handrail reaction force under condition C was the largest after 30% of the cycle. Regarding condition A and B, it decreased to less than half at 50% of the cycle and was nearly zero at 100%.

Furthermore, the COP trajectories in the anterior-posterior direction under condition A of these two patterns are shown in Fig. 8. The COP position of type 1 was close to the heel, and moved slowly during the entire cycle. In the case of type 2, it was relatively far behind the heel at the beginning, then quickly moved across the heel and almost reached the position of the ankle at the end of the cycle.

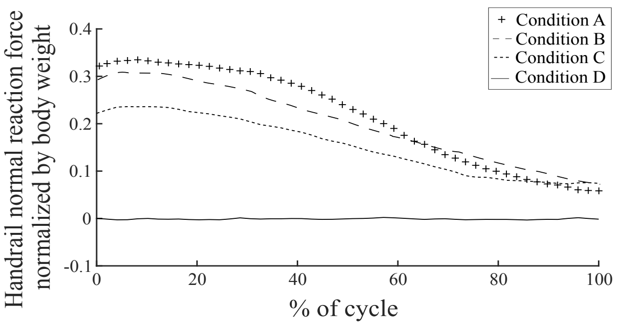
All five participants acknowledged that performing the STS movement under condition C was the easiest. In contrast, four participants selected condition A was the hardest while one participant selected condition B.

## IV. DISCUSSION

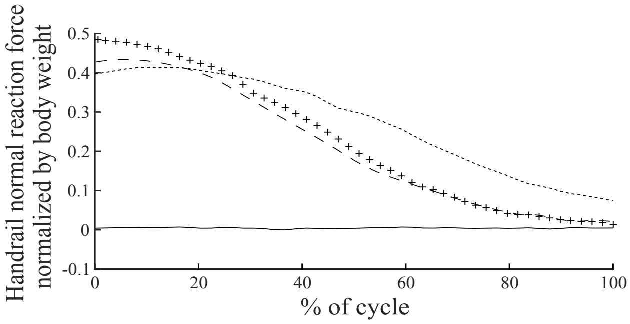
For every condition, the maximum of the joint moment was observed almost immediately after leaving the seat. Hence, the posture right after seat-off is discussed. The balance of the single joint moments can be expressed by the formula (3) as follows:

$$M_j + M_g + M_r - I\ddot{\theta} = 0 \tag{3}$$

where, $M_j$ represents the internal moment of the joint, $M_g$ represents the moment generated by the regions of the body over the joint in question, $M_r$ represents the moment generated by the handrail reaction force, and $I\ddot{\theta}$ is the rotation moment of the regions of the body over the joint in question, respectively. In this experiment, the rotation moment is relatively small and not taken into consideration.




(a) Type 1




(b) Type 2

Fig. 7. Example of two types of handrail reaction forces

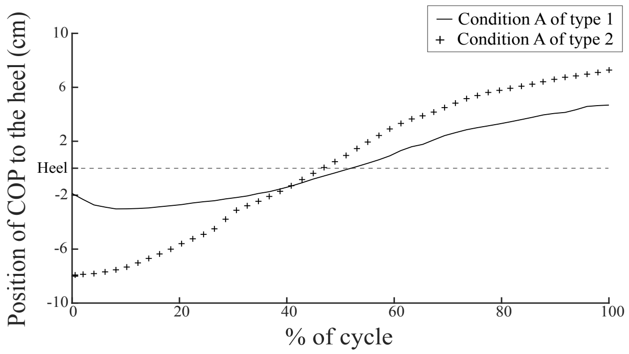



Fig. 8. Example of two types of COP offset under condition A. A positive value indicate that the COP is in front of the heel, while a negative value indicates that it is behind the heel.

Firstly, we discuss the differences in the maximum hip moments among the conditions. As shown in Fig. 9, for conditions B and C, the COG of the upper body is horizontally near the ankle joint because of the 30° forward flexion. Given that the COG of the body is far away from the hip joint, a large magnitude of the moment is generated. In the case of condition A, the moment generated by gravity is very small when considering the short distance between this force and the hip joint. The experimental results are consistent with our expectation and the hip moment was the smallest for condition A. Furthermore, the grip position is far away from the hip joint under condition C, which generates a relatively large moment when compared with condition B, and results in a great compensation for the moment generated by gravity. Therefore, the hip moment in the case of condition C was

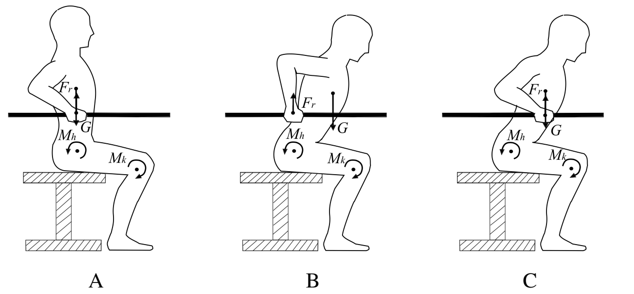



Fig. 9. Forces and joint moments for three conditions ($F_r$: handrail reaction force, $G$: gravity force of the trunk, $M_h$: hip joint moment, $M_k$: knee joint moment)

expected to be smaller than that for condition B. However, no significant difference was observed between these two conditions in the experiment.

Secondly, the maximum knee moments are discussed. The moment generated by gravity is the largest for condition A due to the long distance between the COG of the upper body and the knee joint. Comparing conditions B and C, the point of the handrail reaction force for condition B is further away from the knee joint, thus resulting in a larger reaction moment. Therefore, the maximum knee moment for condition B is the smallest among the three conditions, which is consistent with the results of the experiment.

Moreover, the use of the handrail differed among participants during the STS movement. According to the two types of the reaction force curve and COP trajectory shown in Fig. 7 and Fig. 8, two strategies for use in the STS movement under condition A and condition B are proposed. Strategy 1 is described as supporting the body with handrails as long as possible. This strategy is effective for reducing the joint moments of the lower limbs during the entire period of the STS movement. Furthermore, this also results in a small and slow movement of the COP as represented by the solid curve in Fig. 8. However, the participants who used strategy 2 tended to apply a strong force to the handrails when their hip left the seat and the COP quickly moved from the posterior position to the anterior position. As such, the handrails were used to reduce the maximum hip moment needed during seat-off and to make it easier to leave the seat.

For most participants, the smallest hip moment occurred under condition A, while the smallest knee moment was observed for condition B. However, according to the answers from the participants, condition C was subjectively regarded as the easiest. These results suggest that subjectively easy STS movement is not realized by minimizing the moment of single joints, which is similar to the conclusion given by Chihara et al. [17]. In condition C, the grip position was above the ankle joint, and the trunk was tilted 30° forward. Therefore, the grip position and the COG of the body were always within the base of support during the STS movement. As a result, the participants were freely able to control the force applied to the handrails until the end of the STS movement with great stability. This is likely one of the reasons that condition C was perceived to be the easiest for the performance of the STS movement.

## V. CONCLUSIONS

In this study, the effects of grip position on handrails and the trunk-tilt angle were investigated during STS movement for the use of bilateral handrails. While the importance of these parameters were known in the earlier studies, their combinations have not been thoroughly studied under controlled settings. Throughout the experiment, lower-limb joint moments were compared among three conditions for different grip positions and trunk-tilt angles. The condition where the grip position was above the greater trochanter and participants stood up from an erect sitting position resulted in the smallest hip joint moment, while the condition where the grip position was above the greater trochanter but with a trunk-tilt angle of 30° resulted in the smallest knee joint moment. The subjectively easiest movement occurred under the condition where the grip position was above the ankle joint and the trunk-tilt angle was 30°. The results facilitate the determination of the optimum conditions such that the burden on the lower limbs is minimized.

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