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Original Article

Coordination between Trunk and Ankle during Sit-to-stand Task in Healthy Young Subjects

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Sit-to-stand (STS) requires inter-segmental coordination between the upper body and lower limbs to shift the body's center of mass forward and upward, while also maintaining balance over the small base of support. Specifically, coordination between the trunk and ankle might be important to perform STS more efficiently. The present study aimed to determine the interaction between the trunk and ankle during an STS task. Fifteen healthy young subjects participated in this study. To assess the STS task, we used a motion analysis system with 4 cameras that were synchronized to a force plate. Five trials were recorded for each subject, who performed the task at slow speed to mimic the STS of persons with disabilities. The mean and standard deviation values were calculated for the total STS task duration and the percentage of total task time at which the kinematic events occurred, including initiation of ankle dorsiflexion (DF) and plantar flexion (PF), maximum angular movement of trunk forward inclination (FI) and ankle DF, maximum angular velocity of trunk FI and trunk backward inclination (BI), and lift off (LO). The total duration of the STS task was 3.30 ± 0.30 seconds. The initiation of ankle DF (29.5 ± 8.4%) and maximum angular velocity of trunk FI (29.9 ± 7.2%) occurred simultaneously before LO. In addition, the maximum angular velocity of trunk BI (64.7 ± 7.9%) occurred at the same time as the initiation of ankle PF (64.7 ± 6.6%). A significant positive correlation was found between the maximum angular velocity of trunk FI and initiation of ankle DF ($r = 0.89$, $p < 0.01$), and between the maximum angular velocity of trunk BI and initiation of ankle PF ($r = 0.49$, $p < 0.01$). These findings indicate that inter-segmental interaction between trunk and ankle motions might help healthy young subjects perform STS with more effective LO and achieve sufficient balance after LO.

Key words : sit-to-stand task; inter-segmental interaction; trunk motions; ankle motions

1 Introduction

Sit-to-stand (STS) task is a common skill of daily living and an important measure of physical function. Inability to effectively perform STS task can lead to dependence in daily activities among disabled persons[1]. This mechanically demanding task requires inter-segmental coordination between the upper body and lower limbs to control the body's center of mass (CoM) while maintaining balance over the small base of support[2-5].

According to basic kinematics, STS is initiated with trunk forward inclination (FI) that brings the CoM forward, within the area supported by the feet[6, 7]. During the trunk FI, ankle dorsiflexion (DF) stabilizes the feet on the floor and also indirectly contributes to the angular acceleration of trunk FI[8]. In this manner, acceleration of trunk FI in the presence of feet stability generates the horizontal momentum in the CoM prior to lift off (LO)[9]. As demonstrated by Yu et al.'s study, the CoM cannot achieve adequate horizontal momentum without ankle DF, which curtails the effective LO[10]. After LO, trunk backward inclination (BI) coordinates the horizontal momentum of the CoM to achieve quiet standing[10]. During trunk BI, ankle plantar flexion (PF) acts to stabilize the feet and assist the trunk BI to decelerate the horizontal momentum[8, 9, 11]. Inability to control the horizontal momentum of the CoM results in forward falling when ankle PF is absence or insufficient[9].

In terms of coordination, trunk motions (FI and BI) might be complemented by ankle motions (DF and PF) to generate the horizontal momentum of the CoM before LO and to control this momentum after LO. Therefore, coordination between the trunk and ankle motions is an im-

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portant factor in the STS task to produce effective LO and achieve sufficient standing balance after LO. However, the initiation of ankle motions and its relation with trunk motions has not been fully clarified. Therefore, this present study aimed to determine the kinematic relationship between trunk and ankle motions during STS task in healthy young subjects. The findings of this study can be used in rehabilitation to improve the efficiency of STS task in persons with functional disabilities.

2 Methods

2.1 Subjects

A convenience sample of 15 healthy students (9 males, 6 females) with no history of neuromuscular disorders, and who were 20-22 years old, was selected for the present study. The average height and body mass index of these subjects were 166.8 ± 5.8 cm, and 21.8 ± 1.7 kg/m^2, respectively. This research study was conducted under the approval of the ethics committee of the Osaka Prefecture University (2012-PT11). The purpose of this study was explained to each subject, and their written consent was obtained.

2.2 Motion procedures

The subjects sat on a hard surface stool, which was set to the height of the subject's knee joint in the sitting position. The size of the support surface of this stool was 30 cm wide × 25 cm long.

Each subject performed the STS task barefoot and their arms were folded across the chest to minimize differences due to movement of the upper limbs. Both feet were kept shoulder width apart. The task began with the subject's trunk upright and in the vertical shank position. Subjects were asked to look forward and start the task without changing the position of their feet. The task ended with the subject standing motionless. The subjects performed the slow task, as faster STS creates a shorter flexion phase and less trunk flexion[12-14]. Moreover, the STS task in most disabilities is characterized by slow speed[15, 16]. Before data collection, subjects practiced slow STS for approximately 5 minutes until they could smoothly perform the task. A metronome was set at 40 beats per minute to maintain an appropriate speed, needing to rise in 3 seconds.

2.3 Data analysis

To assess the STS task, we used a motion analysis system (Kinema Tracer, Kissei Comtec) with 4 cameras (30 Hz) that were synchronized by 1 force plate (100 Hz) (TF-3040-A, Tec Gihan). Two cameras were placed on each side of the subject, one perpendicular and one oblique to the sagittal plane of the subject's body. The force plate was placed beneath the stool to measure the time at which the subjects lost contact with the seat (Fig. 1). Ten reflective markers were placed bilaterally at the acromion process, greater trochanter, lateral tibial condyle, lateral malleolus and the lateral aspect of 5th metatarsal. All markers had a 5 cm black base to maximize the contrast between the marker and the subject's skin. Five trials were recorded for each subject while rising at the practiced speed without using metronome. Three trials with a total task time closest to the mean total time were selected for each subject for analysis.

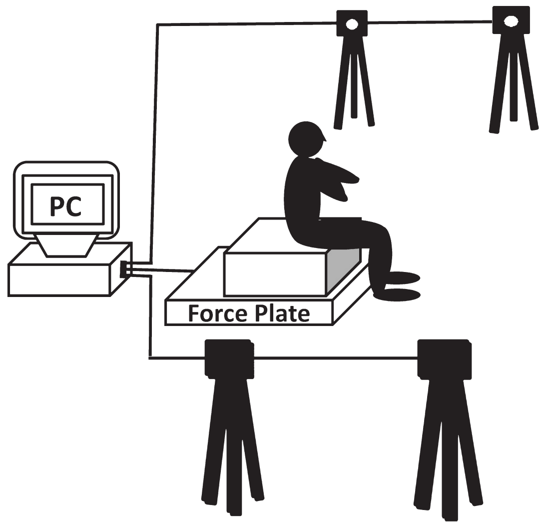

Fig. 1 Schematic view of the subject's position relative to the cameras and force plate.

The sagittal angular movement and angular velocity were calculated. All these data were normalized from the beginning of the STS task (0%) to the endpoint of the STS task (100%). The beginning of the STS task was represented by the time at which the magnitude of the horizontal velocity at the midpoint between the acromion markers was more than 5% of its peak value[8]. The time at which the magnitude of the hip extension's angular velocity first reached 0 m/s was considered to be the endpoint of the STS task[2]. Accordingly, angular movement of the hip was defined as between the line from the midpoint of acromion process to that of greater trochanter and the line from the greater trochanter to that of lateral femoral condyle. The time at which the magnitude of the vertical force on the force plate first reached its lowest point was defined as LO. The task was divided into the before LO and after LO phases.

Regarding angular movement, angles that included the trunk and ankle were collected. Several previous studies[17-19] have demonstrated that healthy subjects exhibit significantly different asymmetry during STS task. To control the bias of bilateral asymmetric movement, an original model was used to define each angular movement

(Fig. 2). First, the midpoints between the bilateral reflective markers, which included the acromion process, greater trochanter, lateral tibial condyle, lateral malleolus and the lateral aspect of 5th metatarsal, were set and each angular movement were calculated. Angular movement of the trunk was defined as the angle between lines from the midpoint of the acromion process to that of the greater trochanter, and the vertical line through the midpoint of the greater trochanter. In a similar way, angular movement of the ankle was defined as movement between the line from the midpoint of the lateral malleolus and that of lateral tibial condyle, and the line from the midpoint of the lateral malleolus to that of the lateral aspect of the fifth metatarsal head. We then calculated the mean and standard deviation values for the total STS task duration and the percentage of total task time at which the kinematic events occurred, including the initiation of ankle motions, maximum angular movement of trunk FI and ankle DF, maximum angular velocity of trunk motions and LO. In this study, the initiation of DF and PF were especially difficult to identify accurately using the plot of the ankle angular displacement. We therefore used the angular velocity of ankle motion to define the initiation of ankle DF. The time at which the magnitude of angular velocity of ankle DF fell outside the mean ± 2 SD of 1 second of angular velocity during the static initial posture was regarded as initiation of ankle DF. Similarly, the initiation of ankle PF was regarded as the time at which the magnitude of angular velocity of ankle PF fell outside the mean ± 2 SD of 1 second of angular velocity during the static initial posture.

To determine the relation between trunk and ankle motions, the movement pattern of each motion and timing of kinematic events were evaluated. Descriptive statistics were obtained using SPSS version 23. A Pearson's correlation coefficient was computed to assess the correlation between the percentages of total task time for the maximum angular velocity of trunk motions and the initiation of ankle motions. A difference was considered statistically significant when the P-value was < 0.05.

3 Results

3.1 STS duration

The mean total time of the STS task was 3.30 ± 0.30 seconds. The duration of the before and after LO phases was 1.31 ± 0.29 seconds and 1.98 ± 0.25 seconds, respectively.

3.2 Kinematic events

Figure 3 illustrates the order of the kinematic events during the STS cycle. The initiation of ankle DF (29.5 ± 8.4%) and maximum angular velocity of trunk FI (29.9 ± 7.2%) occurred simultaneously before LO. In addition, the maximum angular velocity of trunk BI occurred at the same time (64.7 ± 7.9%) as the initiation of ankle PF (64.7 ± 6.6%). Furthermore, trunk FI and ankle DF reached the maximum angle after LO (39.6 ± 7.0%) at 42.9 ± 6.9% and 54.3 ± 6.9%, respectively.

There was a significant positive correlation between the percentages of the total task time for the maximum angular velocity of trunk FI and the initiation of ankle DF

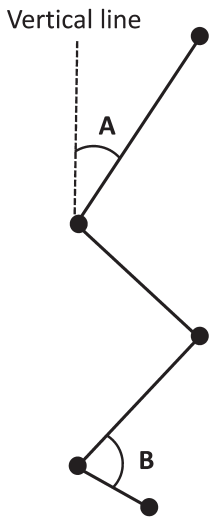

Fig. 2 The angular movement definition for each joint.

∠A: Trunk, ∠B: Ankle. Gray points represent the reflective markers, and black points represent the midpoints between markers on the bilateral acromion process, greater trochanter, lateral tibial condyle, lateral malleolus and the lateral aspect of fifth metatarsal.

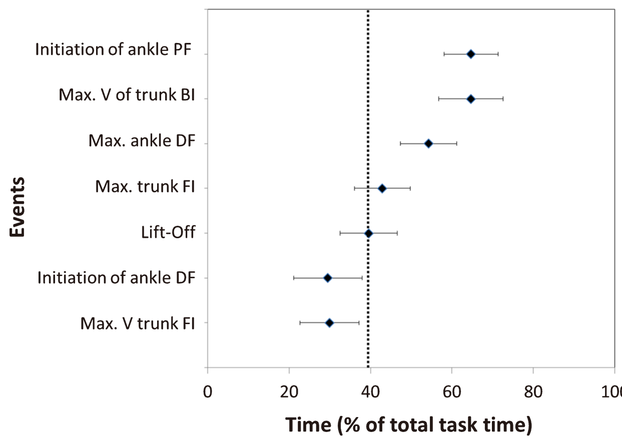

Fig. 3 The order of kinematic events during the STS task.

Values are expressed as the mean percentage of the total task duration. PF; Plantar Flexion, Max; Maximum, V; Angular Velocity, BI; Backward Inclination, DF; Dorsiflexion, FI; Forward Inclination.

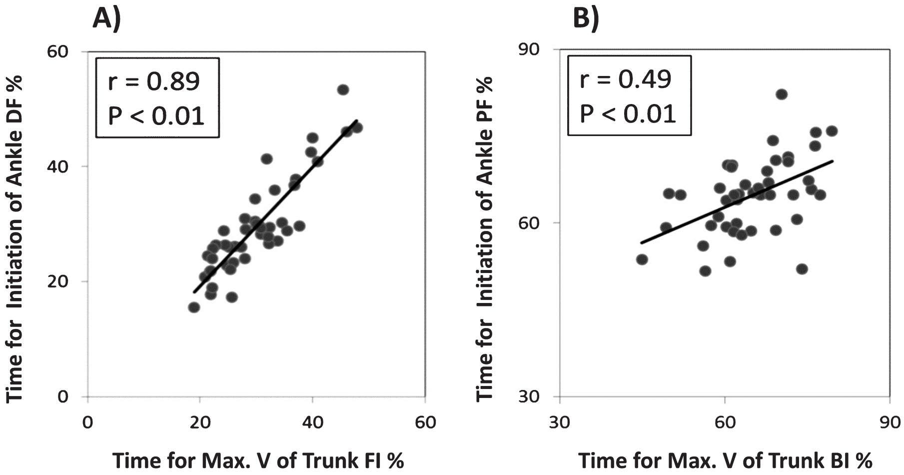

Fig. 4 The correlation between trunk and ankle motions.

A) The correlation between the percentages (%) of the total task time for maximum angular velocity of trunk forward inclination and the initiation of ankle dorsiflexion, B) The correlation between the percentages (%) of the total task time for maximum angular velocity of trunk backward inclination and the initiation of ankle plantar flexion. DF; Dorsiflexion, Max; Maximum, V; Angular Velocity, FI; Forward Inclination, PF; Plantar Flexion, BI; Backward Inclination.

($r = 0.89$, $p < 0.01$) (Fig. 4A), and also between the percentages of the total task time for the maximum angular velocity of trunk BI and the initiation of ankle PF ($r = 0.49$, $p < 0.01$) (Fig. 4B).

4 Discussion

The purpose of this study was to determine the kinematic relation between trunk and ankle motions during STS task in healthy young subjects. The subjects performed slow STS, which is typically observed in persons with disabilities, such as cerebral palsy and stroke[15, 16]. In this study, the mean total STS time for healthy young subjects was 3.30 ± 0.30 seconds, which was slower than that in other studies[6, 13]. However, the LO occurred at $39.6 \pm 7.0\%$, which is similar to the results of pervious STS studies that used force plate to determine this event[6, 20, 21]. Therefore, to determine the relation between trunk and ankle motions, the STS task was performed in the same STS pattern as in other studies.

The major findings of this study indicate that STS task in healthy young subjects was performed using two kinematic strategies of trunk and ankle interaction. The first kinematic strategy was the similar timing for the initiation of ankle DF and the maximum angular velocity of trunk FI, which was confirmed by a significant positive correlation. As previously reported, trunk FI and ankle DF produce horizontal CoM momentum during STS task, and the ankle joints provide stability during the trunk's acceleration[8, 9, 11]. In Khelmani et al.'s study, the tibialis anterior stabilized the feet and indirectly contributed to the angular acceleration of trunk FI[8]. In the present study, once trunk FI reached its maximum angular velocity, the ankle's function changed from stability to mobility. Thus, the ankle joints initiate DF to assist trunk FI in producing sufficient CoM momentum, and this strategy might allow healthy young subjects to LO from the seat more efficiently.

The second kinematic strategy was that the initiation of ankle PF occurred when the angular velocity of trunk BI reached its maximum value, which was confirmed by a significant positive correlation. The magnitude of the actual CoM momentum is generally greater than the required CoM momentum[22], and this extra momentum must be limited to achieve adequate balance after LO[23]. In this manner, interaction between trunk BI and ankle PF has been reported as an important factor to control the CoM in relation to the area supported by the feet. In this study, the ankle reached maximum DF and remained unchanged for approximately 10% of the STS task to provide stability for trunk BI acceleration. Similar to the first strategy, the ankle's function changed from stability to mobility once trunk BI reached its maximum angular velocity. Therefore, using this strategy can help healthy subjects achieve sufficient balance after LO. This interaction between trunk BI and ankle PI has been supported by previous studies, in which backward movement of the shank decelerated the horizontal momentum of the CoM after LO[8, 10]. In addition, similar to Schenkman et al.'s study, we observed that the maximum trunk FI angle and ankle DF angle occurred after LO.

In this study, the kinematic strategies of the trunk and ankle interaction were only observed during slow speed STS and may not accurately reflect the interaction during normal STS. Therefore, further STS studies using both normal and slow speeds are suggested to confirm our findings.

In conclusion, the inter-segmental interaction between the trunk and ankle motions might help young healthy subjects produce sufficient horizontal momentum in the CoM, and thereby achieve LO more effectively during STS. Moreover, this interaction might be necessary to control the CoM's momentum after LO, and thereby achieve sufficient balance in the standing position.

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