Biomechanical Analysis of the Sit-to-Walk Series of Motions Frequently Observed in Daily Living: Effects of Motion Speed on Elderly Persons

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Abstract. It is important to clarify the normal biomechanical characteristics of the sit-to-walk (STW) series of motions clear for healthy elderly people. Clarifying the biomechanical characteristics of normal motions is necessary to be able to develop an appropriate intervention to improve physical functions. Eight healthy elderly people performed STW motion at the two patterns of speeds: a fast condition and a slow condition. Kinematic and kinetic data were obtained. Maximal anterior ground reaction force was significantly larger in the fast speed condition. In the fast speed condition, the subjects initiated gait with the hip and knee more flexed. And the center of pressure (COP) moved forward gradually constraining the forward movement of the center of the gravity (COG). In the slow speed condition, the COG movement was slower, so the COP moved backward in order to induce a forward COG movement. In the fast motion it is important to accelerate and control the forward movement of the body.

Key words: Sit-to-walk, Elderly people, Biomechanical analysis

(INTRODUCTION

In previous studies about gait and motions related to gait, a single motion was the focus of the research\textsuperscript{1, 2)}, such as standing up, gait initiation, steady state gait, and gait termination. However, these are parts extracted from a series of motions in those studies. In many studies, the normal biomechanical characteristics of these single motions were analyzed and it has been reported that elderly people and people with disabilities whose motions departed from the normal biomechanical characteristics could easily fall\textsuperscript{3–5)}. However, there is little biomechanical research on the sit-to-walk (STW) as a series of motions\textsuperscript{6)}.

Recently, the task oriented approach is attracting attention in clinics and in the literature\textsuperscript{7)}. The task oriented approach requires therapists and patients to do purposeful and comprehensive tasks in real life environments\textsuperscript{7)}. Clinically, the task oriented approach is adopted not only as a treatment but also as an evaluation. For example, in addition to evaluating physical functions, such as muscle power of the lower extremities and/or static balance, individually\textsuperscript{8, 9)}, task oriented evaluations, such as the Timed Up and Go (TUG) test, are also frequently performed\textsuperscript{10–12)}. Task oriented motion tends to include a series of motions. The TUG test includes STW motion. The biomechanical characteristics of sit-to-walk, which is a component...
of the TUG test, have not been studied in detail, although this series of motions is observed most frequently in daily living. We evaluate subjects who can perform the TUG test in a shorter time as having good dynamic balance, although we don’t know much about the biomechanical characteristics of STW included in the TUG test.

The purpose of this study was to elucidate the normal biomechanical characteristics of the STW series of motion for healthy elderly people. Especially, we focused on how STW biomechanics change when the speed condition was changed. Elucidation of this would lead to new interventions and interpretations of result of the TUG test.

**METHODS**

The subjects were 8 healthy elderly men without any known physical dysfunctions or previous histories that could possibly affect the tasks of this experiment. The mean age was 69.8 ± 3.9 years, mean height was 180.8 ± 2.8 cm, and mean weight was 61.4 ± 6.8 kg. Prior to the experiments, each subject was informed about the study and gave the authors his consent to participate in this study.

We evaluated STW motion. The subjects were instructed to walk 5 m and to press the button of an alarm on the table to stop it ringing. The chair did not have a backrest and an armrest, and the seat was set at the knee height. The starting position was set as the knee flexed at 90 degrees and the feet apart at shoulder width (Fig. 1). The subjects were instructed to stand up and walk as soon as the alarm began to ring. We defined the “fast speed condition” as stopping the alarm ringing after 6 seconds from the beginning of the ringing, and the “slow speed condition” as stopping the alarm ringing after 9 seconds. The subjects practiced these tasks enough to reproduce them smoothly and naturally.

Kinematic data was obtained by measuring the trajectories of 12 reflective markers (RMs) on the landmarks of the subjects’ bodies with a six camera motion capture system VICON 512 3D (Oxford Metrix Ltd.) at a sampling frequency of 120 Hz. By calculating the trajectory of the markers, the angles of each joint and the coordinates of the center of the gravity of the whole body (COG) were obtained in the sagittal plane. RMs were attached to the acromions, greater trochanters, knee joints, lateral malleolus, calcanei, and the metatarsal heads of the 5th toe as landmarks on both sides. Kinetic data was obtained using two Kistler force plates (900 × 600 mm) (Kistler, Ltd.) at a sampling frequency of 600 Hz. The ground reaction force (GRF) data was indicated with $F_x$ as right-left (left is plus); $F_y$ as anterior-posterior (anterior is plus); and $F_z$ as vertical (up is plus). The center of the foot pressure (COP) was obtained with the force plate data. To determine the timing of the initiation of the head movement, a tape switch were placed on the back of the head (Fig. 2). For analyses, we used the Vicon Workstation, ver.3.7 (Oxford Metrix) and Microsoft Excel 2002 for Windows (Microsoft) as analytic software. Kinematic and kinetic data were filtered using a second-order Butterworth low-pass filter at 6 Hz and 50 Hz, respectively.

To compare the fast speed condition and the slow speed condition, a paired t-test was adopted using the SPSS ver. 12.0 for Windows (SPSS Japan). Statistical level of significance was set at $p<0.05$.

**RESULTS**

Typical GRFs of the stance leg from the starting movement of the head to initiating gait of a subject are illustrated in Fig. 2. The horizontal axis of this graph was normalized with 0 as the beginning of the head movement and 100% as the first heel contact. Vertical lines in the graph show the first toe off in the fast speed condition (FT), the first heel contact in the fast speed condition (FH), the first toe off in the slow speed condition (ST), and the first heel contact in the slow speed condition (SH). There was a significant difference in the maximal value of $F_y$ between both conditions (Table 1).

Typical joint angles of the hip, knee, and ankle motions of the first stance leg are illustrated in Fig.
3. Figure 2 and Figure 3 were drawn in the same fashion. When standing up, there was a significantly smaller change in the angle of the hip joint in the fast speed condition than in the slow speed condition (p<0.01 at the first toe off, p<0.05 at the first heel contact); and the subjects initiated gait with their knees more significantly flexed in the fast speed condition than in the slow speed condition (p<0.001 at the first toe off, p<0.05 at the first heel contact) (Table 1).

From the starting movement of the head to the first heel contact, displacement of the COG was analyzed. Displacement of coordinate y was significantly longer in the fast speed condition than in the slow speed condition (p<0.01). In contrast, displacement of coordinate z was significantly longer in the slow speed condition than in the fast speed condition (p<0.01). The COG and COP lines tended to tilt in the direction of the movement more significantly in the fast speed condition than in the slow speed condition (p<0.001) (Table 1).

Figure 4 shows stick figures of the movement of COG and COP of the stance foot from the initiation of the head movement to the first heel contact. Lines represent every 50 ms. White arrows indicate the first toe off; black arrows indicate the first heel contact in the Fig. 4. In the fast speed condition, COP barely moved during standing up, and then gradually moved forward. In the slow speed condition, the COP moved forward during standing
DISCUSSION

There are many reports in the literature on standing up from a chair for elderly people \(^6\), \(^{13-15}\). Recently, some studies about gait initiation for elderly people have also been reported \(^16\), \(^{17}\). Standing up and gait initiation are fundamental motions frequently performed in daily living. Although these motions are actually performed continuously, there are few studies on the STW which deal with this motion as a series of motions. Janssen et al. \(^6\) state in their review that it is important to evaluate the ability to perform not only the sit-to-stand motion but also the STW motion. Kerr et al. \(^18\) investigated the STW phase in reference to the GRFs and peak velocity of the COG. In this study, we focused on the motion speed of STW for elderly people, and the biomechanical characteristics were analyzed.

In this study, only forward GRF was significantly larger in the fast speed condition than in the slow speed condition. All three components of the GRF in the first swing leg indicated a maximum value at the first heel contact of the swing leg, which indicates that acceleration of the whole body is obtained from the sole of the foot. In examining joint angle and the COG-COP data, we found that there is a reverse pendulum-like behavior and a force couple action in the STW motions (Fig. 5). Because of smooth forward movement of COG in the fast speed condition (Fig. 4), only the forward GRF showed a significantly higher value in the fast

| Table 1. Differences between the fast and slow motions |
|-----------------------------------|---------------|---------------|
| GRF                              | Fast motion   | Slow motion   |
| \(F_x\) [%BW]                    | 10.8 ± 2.1    | 10.2 ± 2.0    |
| \(F_y\) [%BW]                    | 27.1 ± 3.4    | 18.9 ± 3.9    | ** |
| \(F_z\) [%BW]                    | 98.7 ± 9.4    | 100.6 ± 8.5   |
| Joint angle of stance leg        |               |               |
| TO hip [deg]                     | 54.4 ± 17.1   | 37.2 ± 18.0   | ** |
| knee [deg]                       | 51.4 ± 9.7    | 24.7 ± 12.8   | *** |
| HC ankle [deg]                   | 27.8 ± 7.9    | 24.0 ± 6.94   |
| knee [deg]                       | 7.0 ± 7.4     | –0.4 ± 8.0    | * |
| ankle [deg]                      | 11.8 ± 17.4   | 22.1 ± 11.7   |
| COG movement†                    |               |               |
| time [s]                         | 0.98 ± 0.14   | 1.44 ± 0.29   | *** |
| \(y\) direction [mm]             | 906.2 ± 82.3  | 817.8 ± 70.6  | ** |
| \(z\) direction [mm]             | 160.3 ± 46.9  | 210.2 ± 24.2  | ** |
| COG and COP inclination‡         |               |               |
| TO [deg]                         | 89.4 ± 4.5    | 83.2 ± 4.3    | *** |
| HC [deg]                         | 105.5 ± 5.9   | 93.8 ± 5.7    | *** |

%BW: % body weight, TO: the first toe off, HC: the first heel contact.
†: from starting movement of head to the first heel contact.
‡: tilt in the direction of the movement.
*: p<0.05  **: p<0.01  ***: p<0.001.

Fig. 4. Movement of the COG and the COP in the sagittal plane from movement initiation of the head to the first heel contact.
speed condition. To achieve this smooth movement in the fast speed condition, the subjects stood up with their hips and knees flexed and initiated gait while gradually extending them. Thus, subjects initiated gait while standing up in the fast speed condition. It seems that it is important to perform coupled movement of COG and COP. In the fast speed condition, COP moved to make the forward moment of COG, and forward acceleration of COG became larger. In the slow speed condition, COP moved forward during standing up to prevent forward acceleration of COG.

From these results of biomechanical characteristics of STW related to motion speed, we think that people who can’t perform STW quickly can’t/don’t have to move COG anterior farther at the first toe off. Anterior COG movement before toe off makes the moment an impulsive force. Thus people who can perform STW quickly have enough muscle power in their lower extremities to bear the impulsive force, and people who can’t perform STW quickly have learned smaller anticipatory postural control due to their age and declining physical functions.

We believe that it is essential to recognize and evaluate the STW motions as a series of motions, because there are many falls that occur in these transient activities[19]. Also, it will necessary to analyze the STW motions in people with hemiplegia or orthopedic pathologies and to compare fallers with non-fallers in future studies.

REFERENCES