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Technical note

Measurement of the total body center of gravity during sit-to-stand motion using a markerless motion capture system

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ABSTRACT

Purpose: In order to evaluate the movement strategy in sit-to-stand (STS) motion, it is necessary to measure the center of gravity (COG). However, there is no established method for enabling this using convenience device in the clinical setting. The purpose of this study was to validate the measurement of the COG during the STS motion using an inexpensive, portable and markerless motion capture system (MLS).
Method: Eighteen healthy adults participated in our study. The coordinates of the joint centers during the STS motion were collected using the Microsoft Kinect system (as a MLS) and the Vicon system (as a marker-based motion capture system [MBS]). The center of mass of each segment—which was calculated based on the segmental mass and length—were synthesized to calculate the COG. The displacement, velocity, acceleration of the COG during the STS motion were calculated from the data obtained using each system and compared between systems.
Results: The two systems showed significant difference in their measurements of displacement in both the vertical and anteroposterior directions. However, in the anteroposterior direction, there was no significant difference in the measurements of either velocity or acceleration.
Conclusion: Our results suggested the validity of the COG in the anteroposterior direction during the STS motion measured using the MLS. The method developed in the present study enables the evaluation of a patient's movement strategy.

1. Introduction

The sit-to-stand (STS) motion is indispensable for converting the posture from a sitting position to a standing position. It is one of the most important functions in the activities of daily living. The decline of the STS ability is associated with falls [1]. The improvement of the STS ability is one of the general goals of rehabilitation [2]. In addition to the time required to perform the STS motion, biomechanical analyses have analyzed the movement strategy employed during the STS motion [3,4].

There are three strategies of STS [5,6]. The first is the force control strategy. In the force control strategy, the progressing speed of the total body center of gravity (COG) is low, and the vertically projected point of the COG must be moved on the base of support during the vertical upward transition of the COG. The second is the momentum strategy. In the momentum strategy, the progressing speed of the COG is sufficiently large. Even if the vertically projected point of the COG has not moved into the base of support when the hips are lifted, the COG can be turned in the vertical direction. The third is a mixed strategy that combines the two previous strategies. Among the three strategies, the momentum strategy is the most efficient because the momentum generated through the movement of the trunk is transferred to the lower limb and smoothly shifts to the new posture without stopping the body [7].

The STS strategy involves the speed of the COG—modifications to the momentum are important for efficiently performing the STS motion. Many older individuals stand from a chair using a force control strategy. In interventions seeking to modify a force control strategy into a momentum strategy, it is necessary to measure the progressing speed of the COG during the STS motion.

Abbreviations: CM, center of mass; COG, center of gravity; JC, joint center; MBS, marker-based motion capture system; MLS, markerless motion capture system; SDK, software development kit; STS, sit-to-stand.

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The COG during the STS motion cannot be subjectively evaluated by the examiner. Moreover, the expense and measurement restrictions associated with three-dimensional marker-based motion systems (MBSs), which can be used to obtain detailed and objective data, have made such systems difficult to use in a clinical setting. In contrast, the Microsoft Kinect system, which can be used as a markerless motion capture system (MLS), which is inexpensive and portable, can be easily applied to measure human movement in the clinical setting without the use of markers. The accuracy of the COG calculated using data obtained by the Kinect system has been validated using an MBS [8]. However, no studies have reported the validity of the measurements of the displacement, velocity, and acceleration of the COG during the STS motion. The aim of the present study was to validate the measurement of the COG during the STS motion using an MLS in order to develop a method for quantitatively evaluating the movement strategy.

2. Method

2.1. Participants

Eighteen young, injury-free individuals (age: 21.0 ± 0.6 years, height: 169.1 ± 7.3 cm, mass: 65.3 ± 13.4 kg, male: 15) volunteered to participate in the present study. This study was approved by the ethics committee of the Hiroshima International University (15–43). All of the participants provided their written informed consent.

2.2. Markerless motion capture system

The Microsoft Kinect v2 sensor (Microsoft Corp., Redmond, WA, USA) was used. A skeleton model (i.e., a stick figure) was obtained directly from the Microsoft Kinect system official Software Development Kit (SDK) v2. Prior to data collection, the Kinect v2 sensor was placed on a tripod 0.8 m above the floor. Data from the Kinect v2 were obtained at 30 Hz using the body-tracking algorithm included in Microsoft SDK. The Kinect camera does not require any calibration; when a participant is in the camera's field-of-view, a stick figure, which reflects the skeleton of the participant, is automatically computed by the associated software program. The stick figure includes 25 points, which represent the estimated joint centers (JCs) (Fig. 1). The anatomical landmarks of the ankle, knee, and hip JCs were used to calculate the ankle, knee, and hip joint angles, respectively. The spatiotemporal location measurements of these JCs were stored on a hard disk drive until further processing using the Mobile Motion Visualizer AKIRA (System Friend Inc., Itsukaichi, Japan); this device has been approved for use in Japan (34B2 × 10008000001).

2.3. Marker-based motion capture system

The data for the MBS system were acquired at 100 Hz using seven-camera Vicon MX (Vicon Motion Systems, Oxford, UK). A total of 33 reflective markers were placed. The locations of the markers included the acromion process, the elbow, the radial styloid process, the top of the iliac crest, the anterior superior iliac spine, the posterior superior iliac spine, the superior aspect of the greater trochanter, the medial and lateral femoral condyles, the midpoint between the greater trochanter and the lateral femoral condyles, the medial and lateral malleoli, the midpoint between the lateral knee joint line and the lateral malleolus, the head of the first and fifth metatarsals, and the calcaneal tuberosity. These anatomical markers were used to construct the coordinate systems for the pelvis, thigh, shank, and foot segments. The JCs of the hip, knee, and ankle were approximated as described in previous studies [7,9,10], as follows. First, we calculated a vector linking both the greater trochanter markers. Second, the JC of the hip was determined at a point interpolated at a distance of 18% of the vector norm from each reflective marker of the superior aspect of the greater trochanter along the vector. The JC of the knee on the frontal plane was located by identifying the midpoint of a line linking the medial femoral condyle marker to the lateral femoral condyle marker. The JC of the ankle was located by identifying the midpoint of a line linking the medial malleolus marker to the lateral malleolus marker. The positions of these markers were obtained using the BodyBuilder software program (Vicon Motion Systems) and the acquired image data. The marker trajectories were stored on a hard disk drive until further processing.

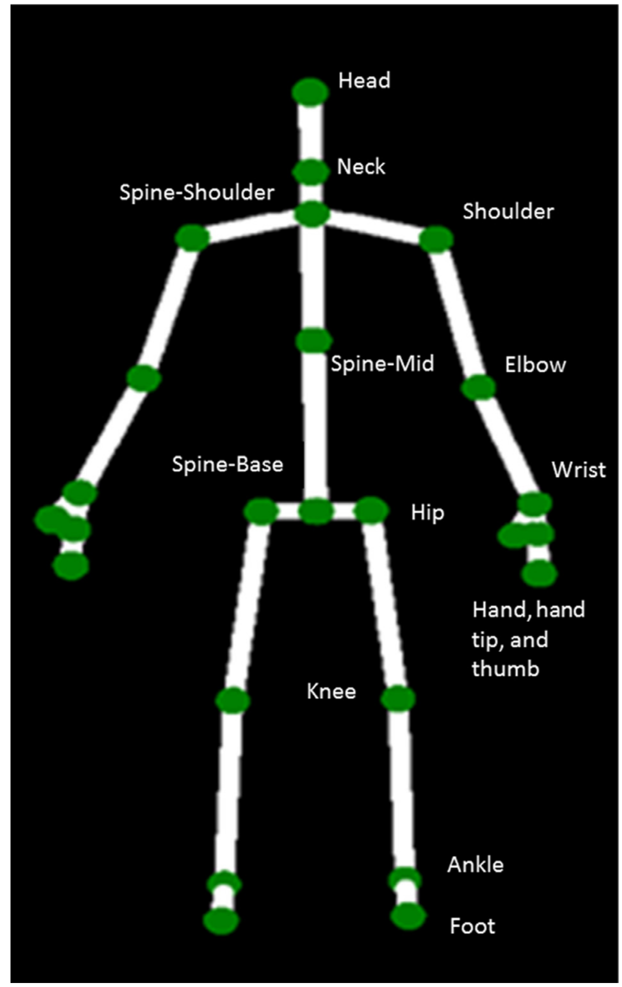

Fig. 1. Skeleton model of Kinect v2.

2.4. Procedure

The participants sat on a chair located 3 m from the Kinect camera (Fig. 2). The height of the chair was set at 40 cm. The STS motion was performed as follows (Fig. 3): first, the participant placed their hands near their ribs and were instructed them not to change their positions. The participants were instructed to place their left or right foot slightly in front of the opposite foot and to face forward. The foot width was arbitrary. Subjects performed the STS motion once before the measurement. During the STS motion, data were collected using the MLS and MBS. The measurement of the STS motion was carried out at a speed of 25 bpm. In total, the measurement was performed five times; however, only the data from the first trial were used in the analysis.

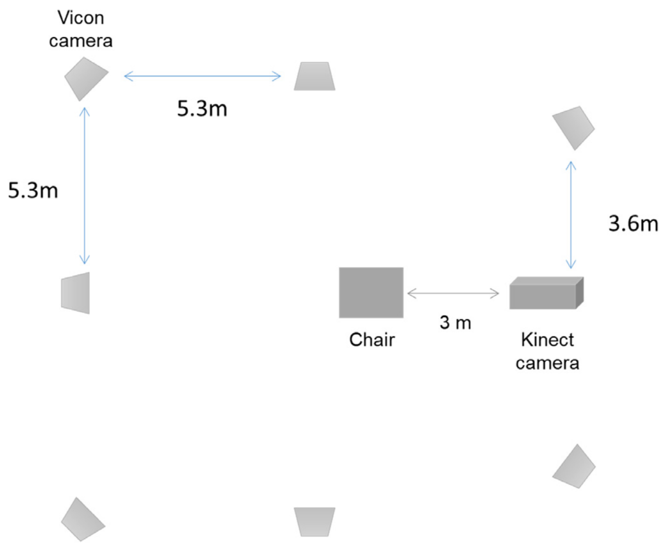

Fig. 2. A diagram of the testing set up. The Vicon cameras were placed at a height of 2.25 m from the floor.

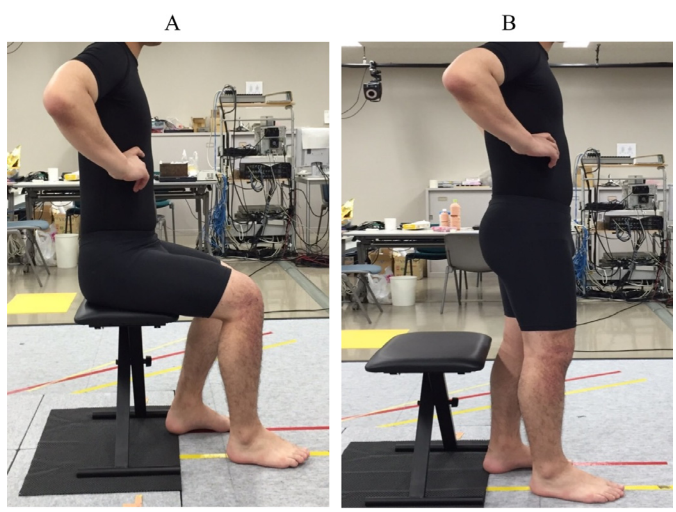

Fig. 3. Task motion. A: Starting posture. B: Final posture.

2.5. Data process

The coordinates of the joint centers in the vertical and anteroposterior directions were collected using both the MLS and MBS. The MBS frequency data was normalized from 120 to 30 Hz in order to facilitate comparison with the MLS. The MLS data were filtered using the methods proposed by Bryant et al. [11] with a 3.0 Hz low-pass filter, to enable the frequency of human gait to be judged as a 2–3 Hz motion [12].

2.6. COG calculation

We used body segment parameters [13] for COG calculation (Table 1). MLS data were used to determine the coordinates of the proximal and distal ends of 7 segments (Head and trunk, bilateral thighs, legs, and feet). Then, we defined the center of mass (CM) of a body segment using the following formulae:

$$x_{CM} = x_p l_p + x_d l_d$$

$$y_{CM} = y_p l_p + y_d l_d$$

where x_{CM} and y_{CM} are the coordinates of CM; x_p and y_p are the coordinates of the proximal end; x_d and y_d are the coordinates of the distal end; and l_p and l_d are the percentages of segmental length from the proximal and distal ends, respectively. COG is the weighted average of the calculated CM of 7 segments, calculated using the following formulae:

$$x_{COG} = \frac{\sum_{i=1}^{7} m_i x_i}{M}$$

$$y_{COG} = \frac{\sum_{i=1}^{7} m_i y_i}{M}$$

where x_{COG} and y_{COG} are the coordinates of COG, x_i and y_i are the coordinates of the i-th segment, m_i is the mass of the i-th segment, and M is the body mass of the 7 segment.

For MBS data, BodyBuilder software was used to calculate COG coordinates. The body segment parameters [13] for the calculation of COG were the same as when using MLS data.

2.7. Statistical analysis

The displacement, velocity, acceleration of COG in the vertical direction and the anteroposterior direction were calculated. The results obtained using the MLS and MBS were compared using a paired t-test. The level of significance was set at 5%.

3. Results

The data related to the COG during the STS motion are shown in Table 2 and Fig. 4. Significant differences were observed between the MLS and MBS with regard to the measurements of the displacement and velocity in either direction. There was no significant difference in the velocity or acceleration in the anteroposterior direction.

4. Discussion

The displacement, speed, and acceleration of COG during the STS motion were measured using the MLS and MBS, and the measurements were compared. Significant differences were found between the two systems in the measurements of displacement;

Table 1
The body segment parameters.

Body segment	Segment definitions		Segmental mass (m)/total body mass (M)	CM/segment length	
	Proximal end	Distal end		Proximal	Distal
HAT	Head	Spine-base	0.678	0.626	0.374
Thighs	Hip	Knee	0.1	0.433	0.567
Legs	Knee	Ankle	0.0465	0.433	0.567
Feet	Ankle	Foot	0.0145	0.5	0.5

CM, center of mass; HAT, head and trunk.
These parameter are adapted from Winter [13].

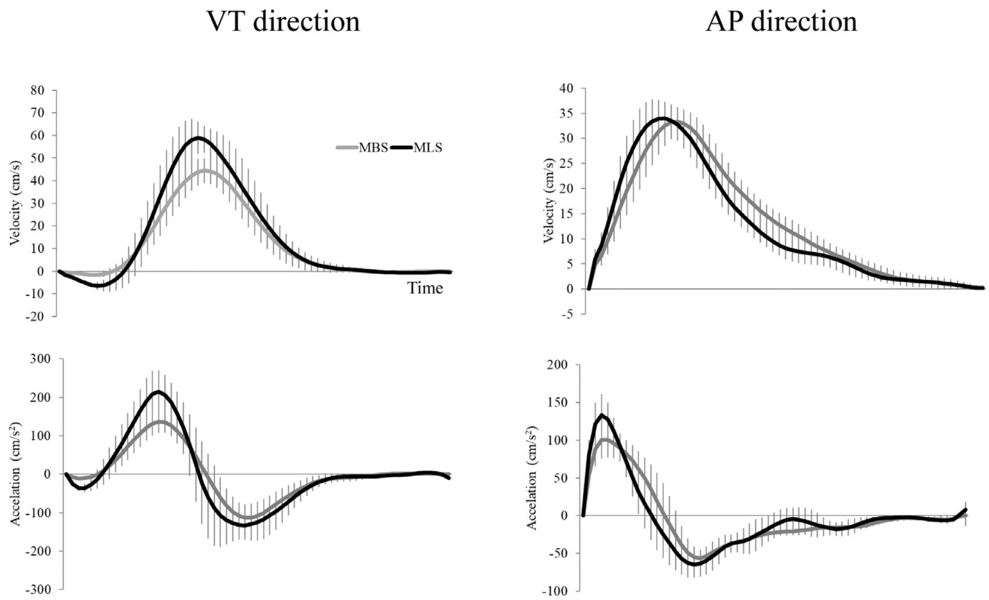

Fig. 4. Transition of the velocity and the acceleration of center of gravity during sit-to-stand motion. COG, center of gravity; VT, vertical; AP, anterior–posterior. Bars means 95% confidence interval; MLS, markerless motion capture system; MBS, marker-based motion capture system.

Table 2
Difference of center of gravity of displacement, velocity and acceleration between markerless and marker-based motion capture systems.

	MLS	MBS	*p*
Displacement in VT direction (cm)	25.19 ± 3.79	32.08 ± 3.02	< 0.01
Displacement in AP direction (cm)	27.01 ± 2.71	25.21 ± 3.02	< 0.01
Velocity in VT direction (cm/s)	14.08 ± 1.54	11.60 ± 1.47	< 0.01
Velocity in AP direction (cm/s)	12.02 ± 1.58	12.67 ± 1.80	0.256
Acceleration in VT direction (cm/s^2)	0.66 ± 0.57	0.19 ± 0.25	0.003
Acceleration in AP direction (cm/s^2)	−2.77 ± 2.18	−2.24 ± 1.71	0.423

COG, center of gravity; AP, anterior-posterior; MLS, markerless motion capture system; MBS, marker-based motion capture system; VT, vertical.

however, the measurements of velocity and acceleration in the anteroposterior direction did not differ to a statistically significant extent.

In the previous study, the position, velocity and acceleration of the COG in the vertical direction can be obtained from the coordinates of the center of mass, which can be calculated using Kinect data [14]. However, the reliability of the results of the previous study was considered to be poor because it only included three subjects and the results were not compared with highly accurate reference standards; furthermore, the authors of the previous study did not perform a statistical analysis. In contrast, 18 subjects participated in the present study and a statistical analysis was performed to compare the data obtained using the MLS to obtained using the MBS. The results of the present study—the methods of which were refined in comparison to the previous study—were highly robust.

No significant difference was found in the velocity in the anteroposterior direction measured by the MLS and MBS. With regard to the velocity in the anteroposterior direction during the STS motion, to the best of our knowledge, there have been no reports on the evaluation of measurement errors using values measured with an MBS. It is unlikely that a small difference observed in our study would represent a serious problem in clinical practice. Additionally, the difference between the MLS and MBS in regard to the acceleration measured during the STS motion, in the anteroposterior direction, was not significant. Our results, which were validated using an MBS, suggest that the COG during the STS motion in the anteroposterior direction could be visualized using the MLS.

Other authors have classified movement strategies differently to the classifications that we applied in the present study [15,16]. For example, one study suggested that the STS movement strategy should be classified into the following three strategies: “healthy” momentum transfer, exaggerated trunk flexion, and dominant vertical rise [16]. In this way, the STS strategy is mainly classified based on kinematic data [17]. The kinematic data obtained by the MLS in relation to the trunk and lower limb joint angle have been validated [18–20]. Our results and the findings from previous studies show that the COG during the STS motion could be visualized using the MLS.

The STS strategy depends on the height of the chair and/or impairment of the patient [21–24]. Studies have been performed on the effective modification of exercise strategies, as such interventions can lead to the modification of the movement strategy [25]. The level of COG displacement during the STS motion is used as an index for judging the effects of treatment [26]. The results of the present study suggest that the MLS, which can be used to obtain kinematic data, including the COG, will be useful for clinical research. The benefit of our method may be significant to practitioners and coaches/ athletes.

5. Conclusion

In the present study, MLS was used to estimate the COG during the STS motion in healthy adults. These findings suggest that the MLS could be used to determine the COG and to classify the STS strategy.

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