The relationship between energy cost and the center of gravity trajectory during sit-to-stand motion

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Abstract. [Purpose] The purpose of this study was to examine the relationship between energy cost and the formation of the center of gravity trajectory during sit-to-stand motion with asymmetrical foot placement. [Subjects] Nineteen male volunteers were included (age: 21 ± 1 years). [Methods] The subjects moved from a sitting position to a standing position under two different foot placement conditions: (1) 0 degrees of dorsiflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side (P1) and (2) 20 degrees of plantarflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side (P2). Two standing conditions were used: (1) natural movement and (2) instructed movement, with instructions to increase weight bearing on the non-dominant side. The center of gravity trajectory and its jerk cost were calculated at each axis: front and back (jerk-x), right and left (jerk-y), and vertical (jerk-z). [Results] Jerk-x and jerk-y were significantly larger during instructed movement than natural movement in both P1 and P2. Jerk-z was not significantly different between instructed and natural movement in P1 or P2. [Conclusion] These results indicate that energy cost influences the formation of the center of gravity trajectory during sit-to-stand motion with asymmetrical foot placement.

Key words: Sit-to-stand, Jerk cost, Asymmetrical foot placement

INTRODUCTION

Rising from a chair is a frequently performed activity of daily living1). Asymmetrical foot placement affects the center of gravity (COG) trajectory during the sit-to-stand motion, with trunk displacement toward the foot placed behind2). However, the reason for this bias in the COG trajectory toward the backward lower limb is unknown.

There are many studies examining the sit-to-stand motion in patients with hemiparesis3–15). Asymmetry was observed in these studies, with the center of pressure greatly deviating toward the unaffected side. Jerk-x and jerk-y were significantly larger during instructed movement than natural movement in both P1 and P2. Jerk-z was not significantly different between instructed and natural movement in P1 or P2. Jerk-z was not significantly different be tween instructed and natural movement in P1 or P2. Jerk-z was not significantly different between instructed and natural movement in P1 or P2. [Conclusion] These results indicate that energy cost influences the formation of the center of gravity trajectory during sit-to-stand motion with asymmetrical foot placement.

SUBJECTS AND METHODS

This study included 19 male volunteers (mean age: 21 ± 1 years; height: 172.3 ± 5.9 cm, body mass: 66.0 ± 9.0 kg). All subjects provided written informed consent prior to participation, and the study was approved by the Human Subjects Ethics Committee of Tohoku Bunka Gakuen University.
The height of the seat was set as the distance from the floor surface to the caput fibulae using 0 degrees of dorsiflexion (Fig. 1). The subjects moved from a sitting position to a standing position under two different foot placement conditions: (1) 0 degrees of dorsiflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side (P1) and (2) 20 degrees of plantarflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side (P2). The side that could kick a ball easily was considered the subject’s footedness. The distance between the left and right foot in the frontal plane was matched with the length between the left and right anterior superior iliac spines. The subjects stood under two movement conditions: (1) natural movement (N-M) and (2) instructed movement (I-M), with instructions to increase weight bearing on the non-dominant side.

Reflective markers were placed bilaterally on the tip of the acromion process, the greater trochanter, the lateral femoral epicondyle, and the lateral malleolus of each subject. Marker positions were recorded using a Locus system (MA-5000, Anima, Japan) at a sampling frequency of 250 Hz. Two force plates (MG-1090, Anima, Japan) were used: a chair was set on one of the force plates and the subjects placed both feet on the other.

The start and the end of a movement were defined as the time at which the angular velocity of the left hip joint movement exhibited its first and second zero-crossings, respectively. Marker displacement data were smoothed using a moving average of 55 data points. Marker positions were used to calculate joint angles, from which the angular velocity was calculated. The COG was calculated using an original MATLAB program (2014b, MathWorks).

Paired t-tests were used to compare the differences in each parameter between N-M and I-M at each foot placement condition. Differences were assessed using two-sided tests, with an alpha value of 0.05.

Table 1 shows the duration, lift-off time, COG displacement, jerk-x, jerk-y, jerk-z, maximum hip joint angle, and maximum hip joint angular velocity for all conditions.

In P1, the COG displacement upon lift-off during N-M was $-1.3 \pm 0.8$ cm, toward the dominant side, and during I-M was $3.9 \pm 1.6$ cm, toward the non-dominant side. In contrast, in P2, the COG displacement upon lift-off during N-M was $-2.9 \pm 1.3$ cm and during I-M was $1.9 \pm 1.3$ cm. During N-M, the COG of all subjects displaced to the dominant side in both postures.

Both the maximum hip joint angle and the maximum hip joint angular velocity were significantly higher during I-M than N-M for both postures ($p < 0.01$). Moreover, jerk-x and jerk-y were significantly larger during I-M than N-M for both postures ($p < 0.01$). Jerk-z was not significantly different between I-M and N-M for both postures.

DISCUSSION

When the subjects stood up from the chair using N-M, the COG trajectory shifted toward the dominant side of the lower extremity. This concurs with many previous studies. The jerk cost in both the right-left and front-back directions were significantly larger during I-M than during N-M. Thus, the jerk cost increases when the subject intentionally changes the COG. In particular, in the front-back direction, the increase in the jerk cost resulted from an increase in the hip joint angular velocity. Similarly, the fast movement of the trunk is thought to influence the increase in the jerk cost in the right-left direction.

Nelson\(^{22}\) explained that the trajectory is formed based on the principle of minimum energy expenditure within the limits of constraints. Therefore, the jerk cost influences the formation of the COG trajectory during sit-to-stand motion with asymmetrical foot placement. Schneider\(^{23}\) reported that hand-trajectory smoothness changed during the practice

**RESULTS**

**Fig. 1. Asymmetrical foot placement conditions**

P1: Non-dominant: df 0°
Dominant: df 20°

P2: Non-dominant: pf 20°
Dominant: df 20°
of a motor task in which smoothness was quantified by jerk cost; namely, the total jerk cost and the magnitudinal and directional jerk-cost components were significantly less when the slowest hand movements were compared after practice versus during practice.

Gillette and Stevermer\(^2\) also reported that utilizing asymmetric foot placement during a sit-to-stand motion resulted in increased ankle plantarflexion and knee extension in the posteriorly placed limb and decreased ankle plantarflexion and knee extension in the anteriorly placed limb. It is thought that the increase in the torque of the posteriorly placed limb was caused by an increase in weight bearing. In the present study, weight bearing on the posteriorly placed limb occurred on the dominant side, and it increased during the natural sit-to-stand motion in both positions. However, it is thought that the total cost was low compared with the increased weight bearing of the anteriorly placed limb. Fleckenstein et al.\(^26\) reported that during a sit-to-stand motion with a symmetrical foot position, the maximum hip flexion torque increased more when using 75 degrees of knee flexion than when using 105 degrees of knee flexion. The activity of the erector spinae also increased when using 90 degrees of knee flexion and 90 degrees of knee flexion. 5 degrees of dorsiflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side I-M: instructed movement, with instructions to increase weight bearing on the non-dominant side Lift-off time: the time that the buttocks lifted from the chair Center of gravity (COG) displacement: positive values indicate displacement toward the non-dominant side

Table 1. Comparison of parameters between movement conditions at each foot placement

|                            | P1  | P2  |
|-----------------------------|-----|-----|
|                            | N-M | I-M | N-M | I-M |
| Duration                    | s   |     |     |     |
| Lift-off time               | s   | 2.66 ±0.37 ‡ | 2.99 ±0.30 | 2.79 ±0.50 | 3.02 ±0.35 |
| Lift-off time / Duration    | %   | 39.6 ±5.8 | 39.6 ±6.1 | 40.9 ±5.4 † | 37.3 ±5.9 |
| COG displacement            | cm  | −1.3 ±0.8 ‡ | 3.9 ±1.6 | −2.9 ±1.3 † | 1.9 ±1.3 |
| Jerk x                      | m²·s⁻⁵ | 10.1 ±3.5 † | 12.0 ±5.3 | 11.0 ±3.8 † | 17.4 ±9.1 |
| Jerk y                      | m²·s⁻⁵ | 1.1 ±0.8 ‡ | 2.3 ±1.1 | 1.6 ±0.8 † | 4.0 ±1.5 |
| Jerk z                      | m²·s⁻⁵ | 24.0 ±12.0 | 23.2 ±16.1 | 25.0 ±15.4 | 28.9 ±20.4 |
| Maximum hip angle\(^1\)     | deg | 112.1 ±7.4 ‡ | 118.2 ±6.3 | 115.2 ±6.8 † | 124.4 ±7.6 |
| Maximum hip angular velocity\(^1\) | deg s⁻¹ | 70.2 ±12.1 ‡ | 80.3 ±12.2 | 76.6 ±11.5 † | 91.8 ±15.0 |

P1: 0 degrees of dorsiflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side P2: 20 degrees of plantarflexion on the non-dominant side and 20 degrees of dorsiflexion on the dominant side

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