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Original Article

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 jerk 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

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INTRODUCTION

Rising from a chair is a frequently performed activity of daily living[1)]. Asymmetrical foot placement affects the center of gravity (COG) trajectory during the sit-to-stand motion, with trunk displacement toward the foot placed behind[2)]. 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 hemiparesis[3–15)]. Asymmetry was observed in these studies, with the center of pressure greatly deviating toward the unaffected side. However, when the affected foot was placed behind the unaffected foot, near symmetry was obtained. When choosing therapeutic exercises, physical therapists utilize this phenomenon to treat patients with hemiplegia[16–18)]. However, the reason for the achievement of near-symmetry when the affected foot is placed behind the unaffected foot is not understood.

Human movement, such as bipedal walking, is influenced by energy expenditure[19)]. To elucidate whether bipedal walking is a more economical form of movement, scholars have examined the energy expenditure of human locomotion relative to that of other mammalian species. Comparative analyses indicate that at walking speeds, humans expend significantly less energy than most quadrupeds[20)]. It is believed that energy expenditure strongly influences the formation of the COG trajectory during motion.

In contrast to studies of energy expenditure during walking, when the duration of motion is short, the energy cost cannot be measured with oxygen consumption. Flash and Hogan[21)] suggested that the minimization of the mean-squared jerk is a mathematical model of one movement objective, i.e., the production of smooth, graceful movements. Jerk is defined as the rate of change of acceleration[22)]. The concept of movement economy requires some jerk costs to be associated with muscular exertion in movement, with the goal of minimizing some measure of cost within the limits of constraints[22)]. Moreover, some studies indicate that the jerk cost influences the coordination of arm movements[21, 23, 24)].

The purpose of this study was to examine the relationship between the jerk cost and the formation of the COG trajectory during a 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.

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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 marker positions, and then the COG velocity, acceleration, and jerk[21] were computed. The anthropometric data described by Winter[25] were used to calculate the COG. The COG trajectory and its jerk cost were calculated at each axis: front and back (x-axis: jerk x), right and left (y-axis: jerk y), and vertical (z-axis: jerk z). The equation of the jerk cost is shown below:

$$\text{Jerk cost} = \frac{1}{2}\int_0^T \dot{a}^2(t)\,dt \quad \dot{a}\text{: jerk, a: acceleration, T: duration}$$

The start of a movement was defined as the time at which the flexional angular velocity of the hip joint on the non-dominant side crossed the threshold value of 1.5 degree$\cdot$s^{-1}. The end of a movement was defined as the time at which the extensional angular velocity of the hip joint on the non-dominant side fell below 1.5 degree$\cdot$s^{-1}. Moreover, the time at which the floor reaction force of the seat side reached zero was considered the lift-off time, i.e., the time when the buttocks lifted from the seat. The COG displacement along the y-axis was calculated from the difference between the start position and the lift-off position. The parameters were 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.

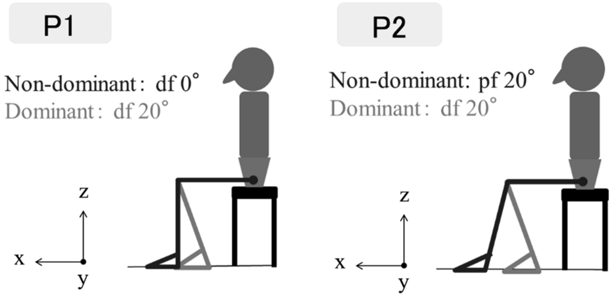

Fig. 1. Asymmetrical foot placement conditions
df: dorsiflexion; pf: plantarflexion

RESULTS

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.

The duration and lift-off time were significantly longer for I-M than N-M in P1 ($p < 0.01$). However, there was no significant difference in the duration or lift-off time between I-M and N-M in P2. However, although the ratio of the lift-off time to the duration in P1 was not significantly different between I-M and N-M, this ratio was greater with N-M than I-M in P2 ($p < 0.05$).

In P1, the COG displacement upon lift-off during N-M was −1.3 ± 0.8 cm, toward the dominant side, and during I-M was 3.9 ± 1.6 cm, toward the non-dominant side. In contrast, in P2, the COG displacement upon lift-off during N-M was −2.9 ± 1.3 cm and during I-M was 1.9 ± 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

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

		P1		P2	
	unit	N-M	I-M	N-M	I-M
Duration	s	2.66 ±0.37 ‡	2.99 ±0.30	2.79 ±0.50	3.02 ±0.35
Lift-off time	s	1.04 ±0.18 ‡	1.18 ±0.22	1.15 ±0.30	1.12 ±0.18
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	$m^2 \cdot s^{-5}$	10.1 ±3.5 †	12.0 ±5.3	11.0 ±3.8 ‡	17.4 ±9.1
Jerk y	$m^2 \cdot s^{-5}$	1.1 ±0.8 ‡	2.3 ±1.1	1.6 ±0.8 ‡	4.0 ±1.5
Jerk z	$m^2 \cdot s^{-5}$	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	$deg \cdot s^{-1}$	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
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
*1 non-dominant side
†$p<0.05$, ‡$p<0.01$

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 in the symmetrical position[27)].

One limitation of this study is that it was difficult to strictly control the duration of the movement. Therefore, the duration was significantly different between I-M and N-M at P1. This difference may have slightly influenced the jerk cost, because the jerk cost is a function of time.

In conclusion, our results suggest that the energy cost influences the formation of the COG trajectory during sit-to-stand motion with asymmetrical foot placement. Moreover, these results suggest that rising from a chair with asymmetrical foot placement may be useful for treating stroke patients with affected lower limbs.

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