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Original Article

Kinematic analysis of slipping when stepping

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ABSTRACT
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Objective: Slipping is a major cause of falls. We investigated body kinematics during slipping when stepping forward.
Methods: Five healthy adults (mean age, 22.2 ± 2.4 years) participated in the study. When the participants stepped forward with the right leg onto a treadmill, one of three types of slips (forward, lateral, or medial) was induced by rapid movement of the treadmill belt. The relationship between the base of support (BOS) and center of gravity (COG) was investigated using three-dimensional motion analysis.
Results: The COG was displaced anterolaterally during all three types of slips. On the horizontal plane, the COG often deviated from the BOS with large medial and lateral slips. Participants most often lost their balance with medial slips, when the COG deviated outside an altered BOS.
Conclusion: Postural control is difficult and is at increased risk of failure during slipping. The risk is greatest in medial slips, followed by lateral slips, and is least in forward slips.
Key words: falls, motion analysis, postural control, base of support

Introduction

Falls can occur in various circumstances, and one-third of older people experience at least one fall annually [1, 2]. Fall-related injuries, such as hip fractures, are associated with morbidity and mortality [3, 4]. Tripping is the most common cause of falls among community-dwelling older people, followed by slipping. These two types of falls account for 57.1% of all falls in men and 69.3% in women and are more common than falls due to dizziness or vertigo [5]. The risk of fall-related injuries is especially high with slipping; approximately 25% of fall-related hip fractures are caused by slips [6].

Exploration of slipping kinematics is important for preventing falls and fall-related injuries. Several studies have investigated slipping kinematics under various conditions: standing on a mat that suddenly moves sideways [7], walking across a force plate that starts moving at a constant speed upon heel strike [8, 9], walking across a surface that suddenly moves forward on rollers or bearings [10, 11], or walking on a slippery surface [11−14]. Little is known about body kinematics during slipping when stepping, or how the slipping direction affects kinematics. We investigated the body kinematics in healthy adults during slipping when stepping forward.

Methods

1. Participants

Five healthy adults without trunk or lower limb impairments participated in the study (mean age, 22.2 ± 2.4 years; mean height, 168.8 ± 5.5 cm; mean weight, 60.8 ± 4.3 kg). The Keiyu Orthopedic Hospital Ethics Committee approved the study protocol, and all participants gave written informed consent before beginning the study.

2. Experimental setup

Slips were artificially produced with a split-belt treadmill (ADAL3D, Techmachine, France) at floor level. The ADAL3D belt can shift back and forth bidirectionally, and is equipped with left and right force plates that record data at 1 kHz. When participants stepped forward on the treadmill belt with the right leg, the belt was abruptly moved at the instance of foot contact to induce a slip. Three slip directions were generated by changing the direction of

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the belt relative to the stepping direction to produce forward, lateral, or medial foot slipping. The belt speed was set at 2 km/h, and we generated small (56 mm/100 ms) and large (167 mm/300 ms) slips in each direction. The belt was moved 10 ms after foot contact produced 5N on the treadmill.

A three-dimensional treadmill gait analysis system (KinemaTracer, Kissei Comtec Co., Ltd., Japan) was used for motion analyses. Markers were placed bilaterally on the acromion, hip joint (at a point one-third of the way from the greater trochanter to the anterior superior iliac spine), lateral femoral epicondyle, lateral malleolus, and fifth metatarsal head. Marker positions were recorded at 60 Hz.

3. Task

The participants began in a standing position with arms crossed in front of the chest and were instructed to step approximately 700 mm forward onto the treadmill with the right leg. To standardize the step size and weight bearing, the participants were instructed to align their head with a target 900 mm in front and to maintain this posture for a few seconds after stepping. Participants practiced the tasks before measurements were attempted. Six slips (large or small and forward, lateral, or medial) were measured for each participant. Although the participants were aware that forward and mediolateral slips would be generated by the treadmill belt, the order of the slip sizes and directions (lateral or medial) was randomized. Participants wore safety harnesses during the task (Figure 1).

4. Analysis

The trajectory of each marker was analyzed for 1,000 ms after slip onset. The virtual center of gravity (COG) position was calculated from the markers [15]. The base of support (BOS) area was calculated as the area bounded by the markers bilaterally placed at the fifth metatarsal head and malleoli on the horizontal plane (Figure 2). COG displacement on the horizontal plane during slips, changes in BOS percentage during slipping, and the relationship between BOS and COG on the horizontal plane were analyzed. For each slip size, the Friedman test was used to determine whether there was a difference in COG displacement and BOS change between the slip directions, and multiple comparisons were performed using the Wilcoxon signed-rank test with Bonferroni's correction. Statistical analyses were performed using IBM SPSS Statistics 23 (IBM Corp., USA). p-Values less than 0.05 were considered statistically significant.

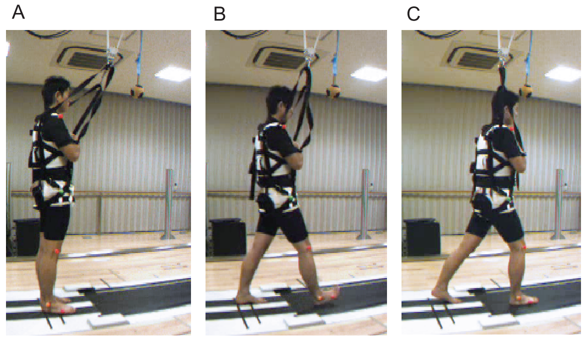

Figure 1. Experimental setup.
Setup for a forward slip is shown.
A. Before stepping, participants stood still with arms crossed in front of the chest.
B. Participants made one step approximately 700 mm forward on the treadmill belt, aligning the head to a target 900 mm in front.
C. Posture at the end of the task. Participants were instructed to maintain the posture for a few seconds.

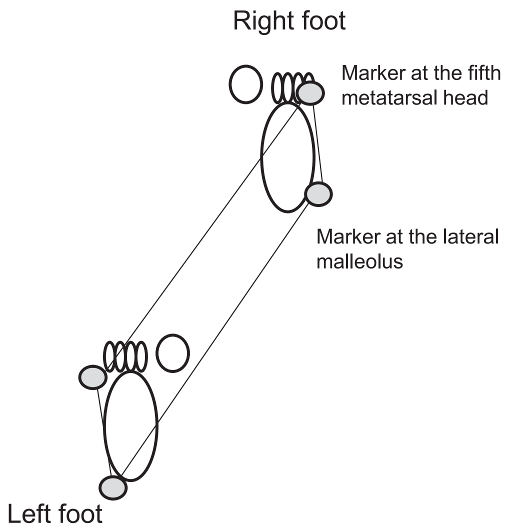

Figure 2. Base of support (BOS) calculation.
The BOS area was calculated as the area surrounded by markers bilaterally placed at the fifth metatarsal head and malleoli on the horizontal plane.

Results

Stick figures illustrating the kinematics during each type of slipping are presented in Figure 3. A stepping strategy, or stepping with the right or left leg to alter the BOS and control balance, was observed in three participants with large lateral slips and in all participants with large medial slips.

1. COG displacement on the horizontal plane (Table 1)

The COG on the horizontal plane was displaced anterolaterally by all slips. Anteroposterior COG displacement by large slips was greater with forward slips than with other types of slips. The difference between types was statistically significant by the Friedman test ($p < 0.05$), but multiple comparisons did not reach significance. The Friedman test did not reveal statistically significant differences in mediolateral

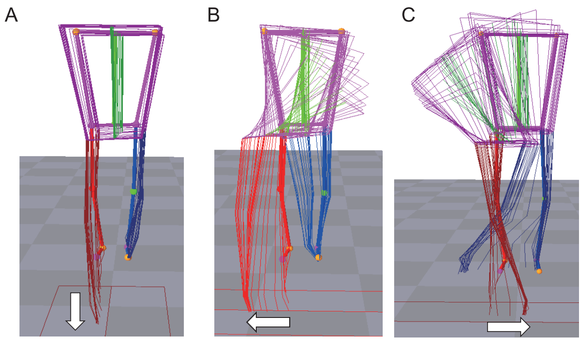

Figure 3. Stick figures of slipping.
A. Forward slip
B. Lateral slip
C. Medial slip
Arrows indicate the direction of slips (direction of the belt). All figures represent large slips.

COG displacement between slip directions for each slip size.

2. BOS change (Table 1)

The BOS area became larger with lateral slips and smaller with forward and medial slips, but there was no statistically significant difference between slip directions.

3. Relationship between BOS and COG on the horizontal plane

The COG deviated from the BOS at the end of large medial and large lateral slips in all participants. In other slips, the COG remained within the BOS. The relationship between the BOS and COG with large lateral and large medial slips is shown in Figure 4. Because the forward foot's position was altered by a

Table 1. Displacement of COG and changes in BOS induced by slipping when stepping forward with the right leg and manifestation of stepping strategy.

		Displacement of COG on the horizontal plane (mm)		Changes in BOS (%)	Stepping strategy *N* (%)
		Anteroposterior direction (Anterior direction as positive)	Mediolateral direction (Lateral direction as positive)		
Forward slip	Small	65±4	10±5	0.93±0.20	0 (0)
	Large	176±25	28±17	0.94±0.40	0 (0)
Lateral slip	Small	68±11	12±5	1.02±0.06	0 (0)
	Large	149±36	35±1	1.13±0.29	3 (60)
Medial slip	Small	62±2	9±2	0.83±0.15	0 (0)
	Large	151±20	21±14	0.67±0.27	5 (100)

Mean ± standard deviation; COG, center of gravity; BOS, base of support.

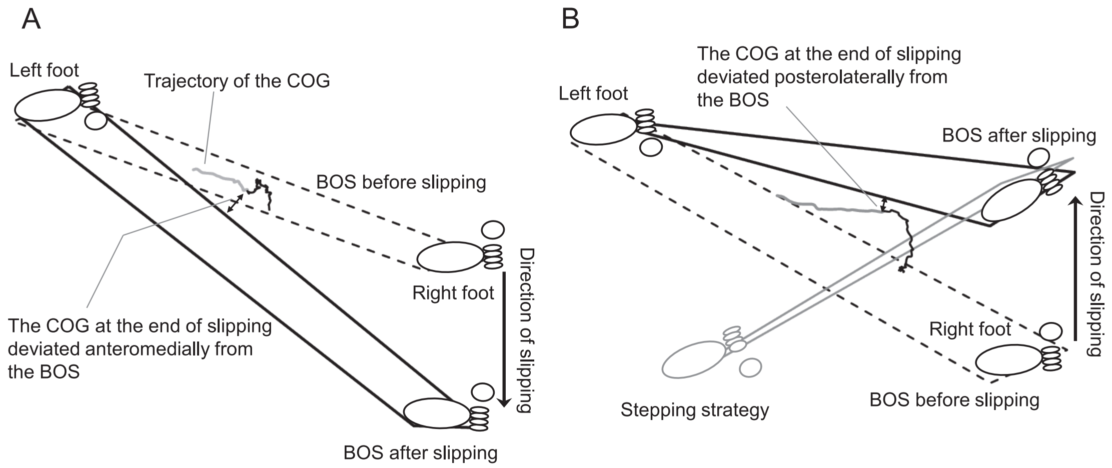

Figure 4. Relationship between the base of support (BOS) and the center of gravity (COG) on the horizontal plane during lateral and medial slips.
The quadrilaterals indicate the BOS: the dotted line is just before an induced 167-mm slip, and the solid line is just after the slip. The trajectory is the projected COG on the horizontal plane. The trajectory from the onset to the end of the slip (0−300 ms) is shown as a thin line and that just after the slip to the end of measurement (300−1,000 ms) is shown as a thick line.
A. In a large lateral slip, the COG deviated anteromedially from the BOS.
B. In a large medial slip, the COG deviated posterolaterally from the BOS. The thin-lined quadrilateral indicates the BOS after the stepping strategy.

slip, the BOS changed in shape and position. The trajectory indicates the COG on the horizontal plane. With lateral slips (Figure 4A), the COG deviated anteromedially outside the BOS just after the slip. The mean ± standard deviation of the vertical distance between the BOS and COG on the horizontal plane was 43 ± 20 mm. With medial slips (Figure 4B), the BOS shifted medially, and the COG deviated posterolaterally outside the BOS just after the slip. The mean vertical distance between the BOS and COG on the horizontal plane was 32 ± 26 mm.

Discussion

In this study, slips were artificially generated when stepping forward. The COG was displaced anterolaterally during all types of slips. The BOS area was largest with lateral slips and smallest with medial slips. The COG remained within the BOS with large forward slips, but deviated from the BOS with large lateral and large medial slips. The COG deviated anteromedially from the increased BOS with lateral slips. In medial slips, the COG deviated posterolaterally from the decreased BOS, and a stepping strategy was observed in all participants with large slips.

The COG must remain within the BOS to maintain a stable upright posture, and a smaller BOS makes this more difficult. A stepping strategy is used when the COG cannot remain within the BOS [16]. In this study, the BOS was smallest with medial slips, and participants could not keep the COG within the BOS. Ankle and hip strategies did not work well with medial slips because the COG was lateral to and behind the body, requiring a stepping strategy to regain postural stability. Although the effect of forward slips on the COG relative to the BOS and balance control during walking has been reported [14], there have been no reports on mediolateral slips. It is a noteworthy finding that slips in the mediolateral direction are associated with greater falling risk.

Lateral stability is reduced in older people who fall compared to those who do not [17, 18]. A lateral body perturbation, such as a medial foot slip, might therefore increase the risk in older people already at risk of falling. Since the lateral fall direction is a hip fracture risk factor independent from other risks, such as decreased bone density [19, 20], medial foot slips might be a strong hip fracture risk factor in older people at risk of falling. In real-world environments, mediolateral slips might occur while walking across a slope, and the risk of falling would increase. Older people at risk of falling should avoid such conditions as much as possible. When unavoidable, fall prevention precautions are needed, such as increasing the BOS by widening the step and decreasing the step length, wearing slip-resistant footwear, or using a walking aid or caregiver assistance. Slippery environments in public spaces should be corrected for drainage and slope.

This study has several limitations. First, the slips were artificially induced by the treadmill, and thus might not be the same as actual slips. Second, the participants were instructed to stop after making a step. Findings should be interpreted with caution, because the study task was not the same as the gait initiation step. Finally, the study did not fully investigate the corrective strategies for the BOS and COG changes induced by the slip and did not explore strategies preventing falls after slips. Further studies, including thorough investigation of corrective strategies and falling mechanisms after slipping, are needed to enhance clinical application.

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