Preliminary Study of Wide Base-of-Support Footwear in Preventing Falls Caused by Lateral Slip during Walking

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The present preliminary study examined whether an increase in the lateral width of footwear (base-of-support width) can reduce the risk of falling caused by induced lateral slip while turning on slippery surfaces. Wide base-of-support (BOS) footwear was designed and manufactured, with lateral widening achieved by fixing a BOS extension, using a planar linkage of 70-mm width on the lateral side of normal BOS footwear. Gait trials were conducted on 16 young healthy male adults. Subjects were instructed to walk in a straight line and to turn 60° to the right on a stainless steel floor covered with glycerol solution. As compared with the normal BOS footwear, the wide BOS footwear reduced the frequency of trials in which fall occurred due to lateral slip by up to 67% and the slip distance and slip velocity of the supporting foot were reduced by up to 40% and 35%, respectively. The results demonstrated the efficacy of increased lateral BOS width in reducing the risk of fall caused by induced lateral slip.

Keywords: slip, fall, base-of-support, footwear, friction

1. Introduction

In Japan, falling accidents have recently become an increasingly serious problem with the mortality rate exceeding that caused by traffic accidents [1], and slipping is one of the leading causes of falling accidents [2-6]. Slipping is likely to occur during transient movements such as turning, in which walking speed and direction are changed, compared with steady-state movement such as linear walking at constant speed. This slipping results due to increased traction coefficient at the shoe-floor interface [7-10]. When slip occurs during turning, the supporting foot slides laterally, in the direction opposite to turning, causing a lateral fall [11]. For elderly people, such lateral falls increase the risk of debilitating and life-threatening femoral neck or hip fractures [12].

In order to maintain postural stability, the displacement and velocity of the body center of mass (COM) must be regulated with respect to the base-of-support (BOS) defined by the feet [13-15]. When standing still, the COM should be located over a stationary BOS to control postural stability. On the other hand, when lateral slip occurs during single support periods during

Fig. 1 Schematic of the positional relationship of the COM and BOS in the frontal plane when lateral slip (to the right) occurs with the right foot. M , moment on the COM; m , whole body mass; g , gravity; F_z , vertical ground reaction force.

walking, the supporting foot moves laterally and the COM may be outside the BOS as shown in Fig.1a. Successful balance recovery, by means of (compensatory) stepping, requires foot movement to arrest the COM within the boundaries of the new BOS established by the compensatory step [14, 16]. However, the slip, which creates a greater distance between the COM and BOS edge, will lead to larger moment acting on the COM in the falling direction caused by the greater moment arm length in the lateral direction (lateral distance between the COM and the center of pressure (COP) of the supporting foot). The COP corresponds to the acting point of the ground reaction force.

It may be effective to increase the lateral BOS width to reduce the risk of falling caused by lateral slip, because increased BOS width would easily restrict the COM within the boundaries of the BOS. Furthermore, because the COP can be located more laterally, any increase in the BOS width would reduce the moment on the COM in the falling direction by shortening the lateral moment arm length (lateral COM–COP difference), as shown in Fig. 1b. Increased BOS width would also provide a time margin for the COP to reach the lateral boundary of the BOS, which would render execution of the lateral step easier. However, an excessive increase in the BOS width could affect the gait and agility during walking or stepping, resulting in foot collision or trip.

The objective of this study was to determine whether increased BOS width would reduce the risk of falling caused by lateral slip during walking. In the preliminary phase, we examined the risk of fall on a slippery floor in young healthy male adults during turning with both normal BOS footwear and laterally widened (by 70 mm) BOS footwear (wide BOS footwear, which was specially designed for this study).

2. Methods

2.1. Preparation of wide BOS shoes

Figure 2 shows normal BOS footwear and wide BOS footwear, which was specially designed for this study. The BOS extension, using planar linkage with stainless steel plates, was fixed to the lateral aspect of commercially available footwear (normal BOS footwear, length: 270 mm) to increase the lateral BOS width. The width of the BOS extension was set at 70 mm. A steel plate was inserted beneath the insole of the normal footwear to equate the weight of the wide BOS footwear, in order to eliminate the effect of weight difference. The weight of each shoe was approximately 1 kg. Nitrile butadiene rubber (NBR) sheet (thickness: 1.8 mm) was affixed to the outer sole of each shoe, and an NBR block (thickness: 10 mm) was also affixed to the sole of the BOS extension. None of the subjects needed packing to fill any space between the shoe and foot.

Fig. 2 Footwear used in this study; a) Normal BOS footwear (left), b) Wide BOS footwear (right)

2.2. Subjects

The study comprised 16 healthy male adults with an average age of 21.4 years (range: 21–26). Mean $\pm$ standard deviation for height and weight of the subjects were 1.74 ± 0.06 m and 62.4 ± 6.4 kg, respectively. This study was approved by the Institutional Review Board of National Nishitaga Hospital, Japan, and informed consent was obtained from all subjects.

2.3. Experimental procedure

Figure 3 shows schematic diagrams of the experimental set-up and movement instructions given to subjects in this study. Gait trials were performed on a 5-m long walkway. Four force plates were installed in the center of the walkway and ground reaction forces were collected at a sampling rate of 60 Hz. Stainless steel flooring ($2 \text{ m} \times 1 \text{ m} \times 2 \text{ mm}$), polished with #400

a. Experimental set-up

b. Turning to the right with the left foot

c. Turning to the right with the right foot

Fig. 3 Schematic diagrams of the experimental set-up and movement instructions to subjects (turning 60° to the right)

abrasive paper, was mounted on the walkway and covered with a solution of glycerol (70 wt.%; viscosity: 19.7 mPa·s). An eight-camera motion measurement system (Motion Analysis Corporation, MAC3D System) recorded three-dimensional motion data at a sampling rate of 60 Hz from 25 reflective markers placed on the body and footwear (toe and heel), based on the Helen Hayes marker set [17].

In order to induce the lateral slip, subjects were instructed to walk in a straight line and to turn 60° to the right with the left or right foot landing on the stainless steel surface, as shown in Fig. 3. Subjects were tested with the normal and wide BOS footwear in separate sessions. The order of testing for the two footwear conditions was balanced across subjects to eliminate the effect of testing order of footwear on the results. Replication of trials for similar conditions was 6 (total: 24 trials for each subject). Subjects were instructed to walk as naturally as possible at a self-selected pace, with a straight gaze and to “do whatever comes naturally to prevent yourself from falling.” Subjects wore a safety harness that was designed to prevent the impact with the floor without otherwise restricting movement that could aid in the control of balance, as shown in Fig. 4. All trials were videotaped.

Fig. 4 Photograph of gait trials on stainless steel floor covered with glycerol solution

2.4. Data analysis

Frequency of trials in which fall occurred was examined for both types of footwear. We defined a “fall” as subjects’ feet being off the floor, followed by the subjects being completely suspended in the harness after losing balance due to slip. Whether subjects had fallen was identified on video data. Vertical ground reaction force F_z data collected from the force plates were also used to determine whether both of subjects’ feet were off the floor ($F_z = 0$ if both feet were off the

floor).

Slip distance and slip velocity (sliding velocity of the supporting foot) were calculated for each trial, using the position data from a reflective marker attached to the toe of the footwear, to examine slip severity. The co-ordinate data of reflective markers were digitally smoothed using a two-order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Slip distance (D) was calculated according to the following formula;

$$D = \sum_{i=m}^{n-1} D(i) = \sum_{i=m}^{n-1} \sqrt{(x_{toe}(i+1) - x_{toe}(i))^2 + (y_{toe}(i+1) - y_{toe}(i))^2} \quad (1)$$

where, i is the frame number, m is the frame number at slip initiation, n is the frame number at slip termination, and $x_{toe}(i)$ and $y_{toe}(i)$ are the co-ordinates of the toe marker.

The velocity of the toe marker in the x and y directions, $v_{toe_x}(i)$ and $v_{toe_y}(i)$, respectively, was calculated according to the following formulae:

$$v_{toe_x}(i) = 60(x_{toe}(i+1) - x_{toe}(i)) \quad (2)$$

$$v_{toe_y}(i) = 60(y_{toe}(i+1) - y_{toe}(i)) \quad (3)$$

thus,

$$v_{toe}(i) = \sqrt{(v_{toe_x}(i))^2 + (v_{toe_y}(i))^2} \quad (4)$$

The maximum value of the velocity of the toe marker was used as the maximum slip velocity v_{max} for the analysis.

Paired t-test was used to identify the differences in the mean values of frequency of trials with fall, slip distance, and maximum slip velocity for both types of footwear. Significance level was set at 0.05. Analysis was performed using SPSS (version 19.0, Chicago, IL, USA).

3. Results and discussion

Figure 5 shows the mean frequency of trials in which fall occurred with both types of footwear when turning with the left foot (Fig. 5a) and right foot (Fig. 5b). Error bars mean standard deviations. The mean values of frequency of fall trials for the normal BOS footwear when turning with the left and right feet were 41.7% (40/96) and 46.9% (45/96), respectively. In contrast, the mean values of the frequency of fall trials for the wide BOS footwear when turning with the left and right feet were 18.8% (18/96) and 15.6% (15/96), respectively. The wide BOS footwear reduced the frequency of fall trials by 55% and 67% for turning with the left and right feet, respectively, compared with the normal BOS footwear ($p < 0.05$). Therefore, it was confirmed that the wide BOS footwear can reduce the risk of falls caused by induced lateral slip when turning on slippery flooring.

There was no significant difference in the mean

friction coefficient of the supporting foot and the floor during slipping (calculated from the ground reaction forces) between the normal BOS footwear (0.038 ± 0.017 for the left foot pivoting; 0.034 ± 0.08 for the right foot pivoting) and the wide BOS footwear (0.041 ± 0.026 for the left foot pivoting; 0.033 ± 0.01 for the right foot pivoting) ($p > 0.05$).

Fig. 5 Frequency of trials in which fall occurred

Increased slip distance and slip velocity of the supporting foot could increase the relative distance between the COM and COP, resulting in loss of postural stability due to an increased moment on the COM in the falling direction. Thus, it has been pointed out that slip distance and slip velocity highly correlate with the risk of falling [18]. Figure 6 shows the relationship between mean values for slip distance and maximum slip velocity of the sliding foot. Error bars mean standard deviations. When turning to the right with the left foot (Fig. 6a), the wide BOS footwear reduced the mean value of slip distance and mean value of the maximum slip velocity by 22.8% and 27.5%, respectively, compared with the normal footwear ($p < 0.05$). When turning to the right with the right foot (Fig. 6b), the wide BOS footwear also reduced the mean value of slip distance and mean value of maximum slip velocity by

40.0% and 34.7%, respectively ($p < 0.05$).

Figures 7 and 8 show successive images of typical trials in which a fall occurred when turning to the right with the left and right feet, respectively. As shown in Fig. 7, lateral slip (to the left) occurred at the pivoting left foot, and then the subject stepped with the right foot to recover the balance. However, a large lateral slip (to the left) again occurred at the right foot, resulting in a lateral fall. On the other hand, when turning to the right with the right foot, a large lateral slip (to the left) occurred at the pivoting right foot, the subject then being unable to make a compensatory step with the left foot resulted in a fall as shown in Fig. 8. As is indicated in Figs. 7 and 8, falls were likely to occur due to a large lateral slip (to the left) of the right foot. When a large lateral slip of the right foot occurs, the moment on the COM in the falling direction increases because the lateral distance between the COM and COP (within the BOS) increases. This would possibly produce difficulty in cross-over stepping with the left foot to recover balance. The wide BOS footwear reduced slip velocity and slip distance as shown in Fig. 6, and therefore the horizontal distance between the COM and lateral BOS edge of the right foot decreased. In addition, the COP may be located more laterally with the wide BOS footwear compared with the normal BOS footwear. Thus, the moment acting on the COM in the falling direction would be reduced by shortening the length of the moment arm in the lateral direction, which would result in a reduction in the frequency of fall with or without compensatory stepping with the left foot.

In this study, it was demonstrated that wide BOS footwear reduces the risk of falling caused by lateral slip when turning. However, the weight of the footwear was approximately 1 kg and the width of the lateral extension of the BOS was large (70 mm); these factors may have affected the gait and agility. In future studies, an optimum (minimum) width for the lateral extension of the BOS, which has the ability to reduce the risk of slip and fall but affects gait and agility less, will be clarified. In addition, a reduction in the weight of the

Fig. 6 Slip distance and maximum slip velocity

Fig. 7 Successive images of trials in which fall occurred when turning with the left foot

Fig. 8 Successive images of trials in which fall occurred when turning with the right foot

footwear will be sought. This study involved only young healthy adults. It would also be necessary to investigate whether wide BOS footwear is effective in older adults to reduce the risk of fall due to slipping.

4. Conclusions

The present study examined whether wide BOS footwear, in which the BOS was extended by 70 mm laterally, reduces the risk of fall caused by lateral slip during turning on a slippery floor. The conclusions are summarized as follows:

- 1) Wide BOS footwear reduced the frequency of fall trials because of lateral slip by 55% and 67% for turning with the left and right feet, respectively, compared with normal BOS footwear.
- 2) When turning to the right with the left foot, wide BOS footwear reduced slip distance and maximum slip velocity during slipping by 22.8% and 27.5%, respectively, compared with normal BOS footwear.
- 3) When turning to the right with the right foot, wide BOS footwear reduced slip distance and maximum slip velocity during slipping by 40.0% and 34.7%, respectively, compared with normal BOS footwear.

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