DEVELOPMENT OF HIGH SLIP-RESISTANT OUTSOLE USING HYBRID RUBBER SURFACE PATTERN TO PREVENT SLIPS AND FALLS ON CONTAMINATED FLOORS

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The present study examined whether a new footwear outsole with tread blocks and the hybrid rubber surface pattern increases slip-resistance and reduces the risk of fall during walking on a liquid-contaminated floor surface. Fourteen adult males participated in gait trials on a stainless steel floor contaminated with a glycerol solution. Subjects were asked to walk straight and turn 180° at the end of the floor to return to the starting position. The frequency of trials with a slip and those with a fall were examined, and the slip velocity and slip distance of the slipping foot were calculated using kinematic data collected from a three-dimensional motion capture system. For comparison, commercially available boots used in food factories and restaurants were also tested. The newly developed footwear reduced the frequency of slips ($p < 0.001$), slip distance ($p < 0.001$), and slip velocity ($p < 0.001$) compared to the conventional boots, resulting in a significantly reduced risk of fall. The results indicate that the rubber outsole with a hybrid rubber surface pattern is effective in preventing slip-related falls during walking on floors contaminated with water or oil.

Introduction

Falls are the leading cause of occupational accidents in Japan (Kawajiri, *et al.*, 2001). Slips are the most frequent event leading to falling accidents (Courtney, *et al.*, 2001; Ministry of health, labour and welfare, 2011). Most slip and fall accidents in a work place occur on liquid-contaminated floor surfaces (Leclercq, *et al.*, 1995; Manning & Jones, 2001)

A high static coefficient of friction (SCOF) and dynamic coefficient of friction (DCOF) are needed at the shoe–floor interface during walking to prevent slip initiation and to stop a slip, if it occurs. Previous biomechanical studies on the safety limits of SCOF and DCOF (Fong, *et al.*, 2009; Grönqvist, *et al.*, 2003; Nagata, *et al.*, 2009) indicated that SCOF and DCOF values > 0.4 are required at the shoe–floor interface to prevent a slip and fall during level walking.

Surface pattern designs of footwear outsoles, including the tread pattern (macroscopic pattern) and surface roughness (microscopic pattern), are helpful to drain liquid from the shoe–floor interface to increase slip resistance, i.e., coefficient of friction (Chang, *et al.*, 2001; Li & Chen, 2005). However, the design criteria for a shoe sole pattern with a sufficiently high SCOF and DCOF on contaminated surfaces was unclear.

Yamaguchi et al. (2012) found that a rectangular rubber block with a rough surface has high SCOF and low DCOF values, whereas a rubber block with a smooth surface has low SCOF and high DCOF values on a smooth stainless steel surface contaminated with a glycerol solution. Based on this finding, they developed a rubber block with a surface pattern of rough and smooth surfaces (hybrid rubber surface pattern, see Figure 1). They demonstrated that the rubber block with the rough surface area ratio *r*, a ratio of the surface area of the rough surface component to that of a single tread block, of 50% had SCOF and DCOF values > 0.4 on the contaminated surface (Yamaguchi, *et al.*, 2012). These results indicate that the hybrid rubber surface pattern would be applicable to the surface pattern of a footwear outsole to prevent slips and falls.

In the present study, new footwear sole, using a hybrid rubber surface pattern, was developed and tested to determine its efficacy for increasing slip resistance and reducing the risk of fall due to a slip on a contaminated floor surface. We hypothesized that the developed footwear, using the hybrid rubber surface pattern reduces 1) the risk of slip occurrence, slip distance and slip velocity when a slip occurs and 2) the risk of fall due to slip during turning on a contaminated surface.

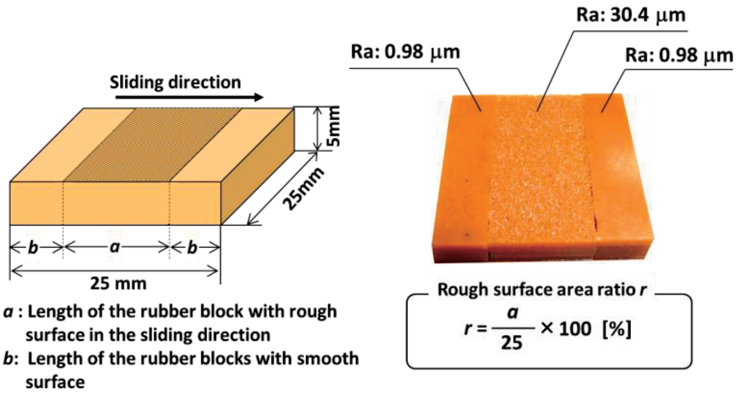

Figure 1. Rubber block with a hybrid surface pattern

Methods

Test footwear

Figure 2 shows the test footwear. Footwear A was a commercially available boot, which is conventionally used in food factories and restaurant kitchens (Figure 2(a): ZONA G3, Kohsin Rubber Co., Ltd., Sendai, Japan). The comparative footwear had tread blocks with a pearskin-finish surface and a round chamfered edge. Footwear B was a sneaker-type footwear with an outsole of tread blocks and the hybrid rubber surface pattern (Figure 2(b)). The footwear B was developed in this study. The ratio of the surface area of the rough surface to that of a single tread block (rough surface area ratio) was 50% for the outsole with the hybrid rubber surface pattern. The outsoles of both types of footwear were made from nitrile butadiene rubber (shore hardness: 58 (A/15) for footwear A; 45 (A/15) for footwear B).

Subjects

The study included 14 healthy adult males with an average age of 23 years (range: 21–25 years). Mean ±standard deviation for height and weight of the subjects was 1.74 ± 0.03 m and 61.4 ± 4.7 kg, respectively. This study was approved by the Institutional Review Board of National Nishitaga Hospital, Japan, and informed consent was obtained from all subjects prior to study initiation.

Experimental procedure

Figure 3(a) shows a schematic representation of the experimental set-up. A stainless steel floor (2 m × 1 m × 2 mm), polished with #400 abrasive paper, was mounted on a walkway and covered with a glycerol solution (glycerin concentration: 70 wt%; viscosity: 19.7 mPa•s). A six-camera motion measurement system (Vicon 370; Oxford Metrics Ltd., Oxford, UK) recorded three-dimensional motion data at a sampling rate of 60 Hz from four infrared-reflective markers attached bilaterally to the toe and heel parts of the footwear.

Subjects were asked to walk straight and turn 180° at the end of the stainless steel floor, then return to the starting position, as shown in Figure 3(b). They were instructed to walk at a self-selected pace and to do whatever came naturally to prevent a falling. Subjects wore a safety harness to help balance. Subjects were tested with the two types of footwear in separate sessions. The order of testing footwear conditions was balanced across subjects. Three replications of the trial session for the same conditions were conducted (total: six trials for each subject). All trials were videotaped.

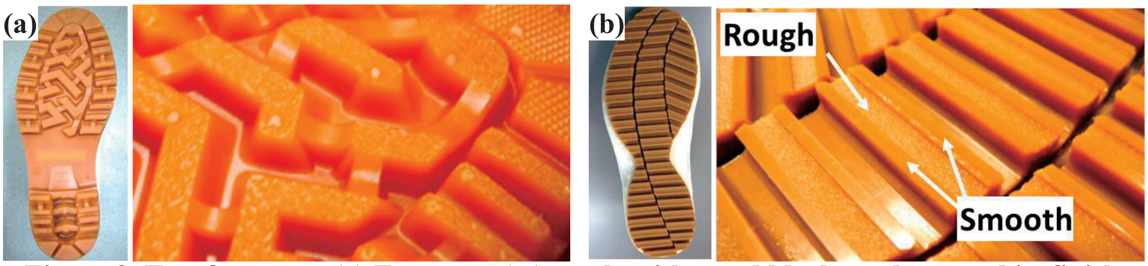

Figure 2. Test footwear; (a) Footwear A (outsole with tread blocks and a pearskin-finish surface); (b) Footwear B (outsole with tread blocks and the hybrid rubber surface pattern)

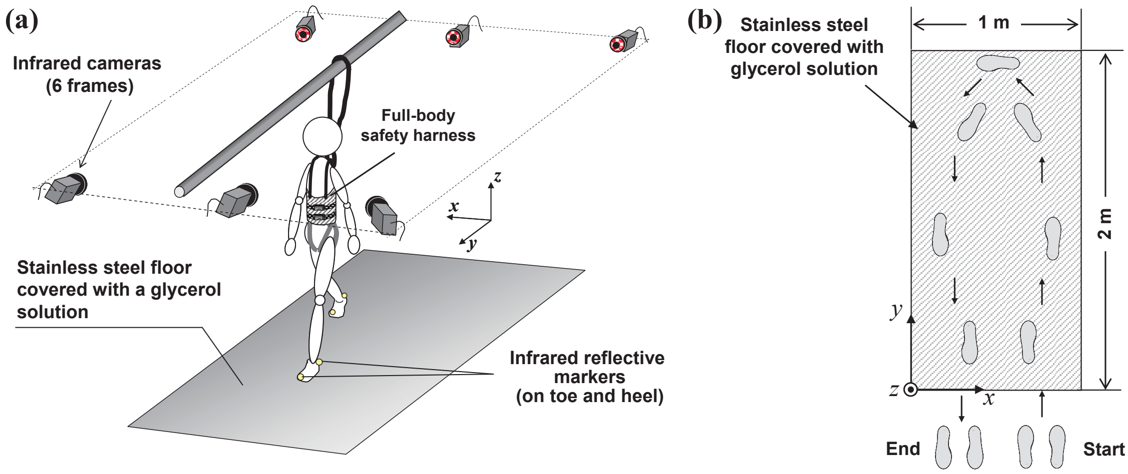

Figure 3. Schematic representation of (a) the experimental set-up and (b) instructed movement; 180° turn after walking straight on stainless steel floor

Data Analysis

The frequency of trials in which a fall occurred was examined for each footwear type. We defined a fall when the subject's feet were off the floor and when they were completely suspended by the harness after losing balance due to a slip. Whether subjects fell or not was identified based on video data. For trials in which it was difficult to identify a fall from the video data, vertical coordinates of the heel and toe reflective markers were used to determine whether both of the subject's feet were off the floor. When the moving distance of the heel marker during the stance phase (from heel-contact to toe-off) was > 6.0 mm, which was the mean value of the marker fluctuation, it was identified as a slip.

Slip distance and slip velocity (sliding velocity of the supporting foot) were calculated for each trial using the position data of the reflective marker attached to the toe part of the footwear, to examine the severity of slip. The coordinate data for the reflective markers were digitally smoothened using a two-order low-pass Butterworth filter with a cut-off frequency of 10 Hz.

The slip distance, D, was calculated by the following formula:

$$D = \sqrt{\left(x_{toe}(n) - x_{toe}(m)\right)^2 + \left(y_{toe}(n) - y_{toe}(m)\right)^2} \qquad (1)$$

where, $x_{\mathrm{toe}}(m)$ and $y_{\mathrm{toe}}(m)$ are the coordinates of the toe markers in the x and y directions at slip initiation, and $x_{\mathrm{toe}}(n)$ and $y_{\mathrm{toe}}(n)$ are the coordinates of the toe markers in the x and y directions at slip termination. The highest value of sliding distance among all slipping steps in each trial was used as the maximum slip distance, D_{max}, for analysis.

The velocity of the toe marker was calculated using the following formula:

$$v(i) = 60\sqrt{(x_{toe}(i) - x_{toe}(i-1))^2 + (y_{toe}(i) - y_{toe}(i-1))^2} \quad (2)$$

where, i is the frame number. The maximum velocity of the toe marker in each trial was used as the maximum slip velocity, v_{max}, for analysis.

The statistical analysis was performed using IBM SPSS Statistics 19.0 (Chicago, IL, USA). The paired t-test was used to identify differences in the mean frequency of the trials with slip, maximum slip distance, and maximum slip velocity as dependent variables for both types of footwear. A significance level of 0.05 was used for analysis.

Results

The mean frequency of trials in which a slip occurred, mean maximum slip distance (D_{max}) and slip velocity (v_{max}) for both types of footwear are summarized in Table 1. The mean frequency of trials with slip for footwear A and footwear B was 97.6% and 66.7%, respectively. A paired t-test indicated that these frequency values were significantly different ($p < 0.001$); therefore, footwear B reduced the frequency of slip occurrence by 30.9 points compared to footwear A. Such a lower frequency of slip occurrence with footwear B was achieved possibly because of higher SCOF at the shoe–floor interface. The statistical analysis indicated that the mean D_{max} and v_{max} values for footwear B were significantly lower than those for footwear A ($p < 0.001$). Footwear B reduced the mean D_{max} and v_{max} values by 97% and 90%, respectively, compared to footwear A. Particularly, the mean slip distance for footwear B was 9.6 mm, which was almost the same as the mean value of the marker fluctuation (6.0 mm); therefore, the slip distance for footwear B was negligibly small. Slip distance and slip velocity are indicators of the risk of fall caused by an induced slip during walking, and greater slip distance and slip velocity are associated with a greater frequency of falls (Brady, *et al.*, 2000; Cham & Redfern, 2002). Therefore, lower slip distance and slip velocity do not lead to a fall with footwear B that could be achieved by higher DCOF at the shoe–floor interface. These results support our first hypothesis.

The mean frequency of trials in which a fall occurred for both types of footwear is presented in Figure 4. The frequency of fall trials for footwear A and B were 54.8% (23/42) and 0%, respectively; no subjects fell while testing footwear B. The result supports our second hypothesis.

Discussion

Superior slip-resistance as well as efficacy in reducing the risk of fall with footwear B, which had the hybrid rubber surface pattern on the tread block of the outsole, was possibly because of high SCOF and DCOF values of the hybrid rubber surface pattern (Yamaguchi, *et al.*, 2012).

As shown in Figure 5(a), when the tread block with the hybrid rubber surface pattern contacts a floor surface covered with glycerol solution, the glycerol solution film is drained and removed because of the high contact pressure by the rough surface asperities, resulting in a direct contact between the asperities of the rough surface component and the floor surface. Thus, SCOF would reach a high value, resulting in a low frequency of slips for footwear B.

Even when a slip occurs because of a high traction coefficient caused by gait characteristics such as large step length (Yamaguchi & Hokkirigawa, 2008; Yamaguchi, *et al.*, 2008), the anterior right edge of the smooth surface component prevents infiltration of the glycerol solution into the contact interface and deformation of the tread block increases the contact pressure at the anterior part of the block (Besdo, *et al.*, 2010), which allows the smooth surface part to contact directly with the floor surface (Figure 5(b)). Therefore, DCOF would reach a high value, resulting in low slip distance and slip velocity for footwear B.

In contrast, footwear A, which has the tread blocks with a pearskin-finish surface, has rounded surface asperities. Therefore, the contact pressure between the asperities and the floor surface was not high enough to drain the solution film from the contact interface, which resulted in a low SCOF value at the slip initiation and DCOF during sliding.

Table 1. Frequency of trial with slip and maximum slip distance and velocity [mean (SD)]

	Footwear A (conventional)	Footwear B (hybrid pattern)	p values
Frequency of trials with slip, %	97.6 (8.91)	66.7 (22.7)	<0.001
Maximum slip distance, m	0.32 (0.16)	0.01 (0.01)	<0.001
Maximum slip velocity, m/s	1.85 (0.87)	0.18 (0.17)	<0.001

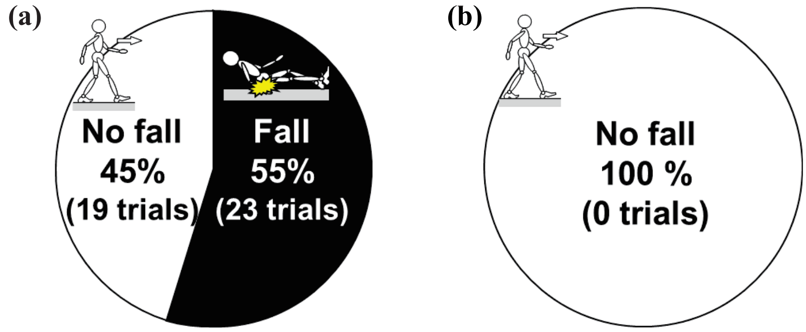

Figure 4 Frequency of trials with fall and without fall; (a) footwear A (conventional); (b) footwear B (hybrid surface pattern)

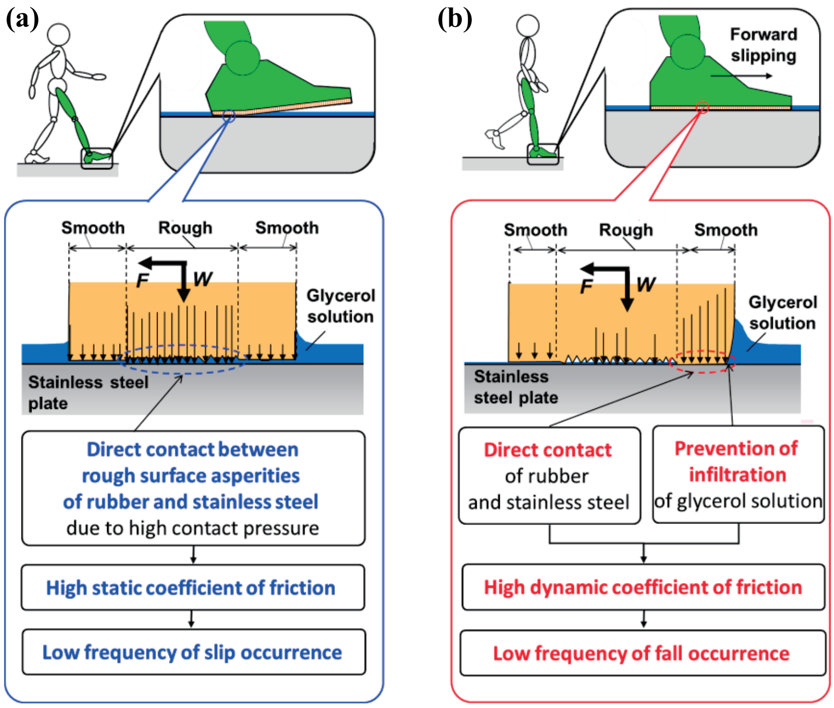

Figure 5: Mechanisms of low slip and fall frequency for the outsole with the hybrid rubber surface pattern; (a) before slipping; (b) during slipping

Conclusions

A new footwear sole, using a hybrid rubber surface pattern, was developed and tested to determine whether it was efficacious in increasing slip-resistance as well as reducing the risk of fall caused by a slip during walking on a contaminated floor surface. The frequency of slips, slip distance, and slip velocity for the new footwear sole were significantly lower than those for the comparative footwear, which resulted in no falls during trials. The results of the current study indicate that the newly developed footwear outsole will contribute to prevent slip and fall accidents in work places.

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