Industrial Health 2014, **52**, 414–423

Original Article

Development of a High Slip-resistant Footwear Outsole Using a Hybrid Rubber Surface Pattern

Takeshi YAMAGUCHI[1*] and Kazuo HOKKIRIGAWA[1]

[1]Graduate School of Engineering, Tohoku University, Japan

Received May 9, 2014 and accepted July 11, 2014
Published online in J-STAGE July 24, 2014

Abstract: The present study examined whether a new footwear outsole with tread blocks and a hybrid rubber surface pattern, composed of rough and smooth surfaces, could increase slip resistance and reduce the risk of fall while walking on a wet floor surface. A drag test was performed to measure static and dynamic coefficient of friction (SCOF and DCOF, respectively) values for the footwear with the hybrid rubber surface pattern outsole and two types of commercially available boots that are conventionally used in food factories and restaurant kitchens with respect to a stainless steel floor covered with glycerol solution. Gait trials were conducted with 14 participants who wore the footwear on the wet stainless steel floor. The drag test results indicated that the hybrid rubber surface pattern sole exhibited higher SCOF (≥0.44) and DCOF (≥0.39) values than the soles of the comparative footwear (p<0.001). Because of such high SCOF and DCOF values, the slip frequency (p<0.01), slip distance (p<0.001), and slip velocity (p<0.001) for the footwear with the hybrid rubber surface pattern outsole were significantly lower than those for the comparative footwear, which resulted in no falls during trials.

Key words: Footwear, Outsole, Rubber, Hybrid surface pattern, Slip and fall

Introduction

Falls are the leading cause of occupational accidents in Japan[1)]. Slip is one of the frequent events leading to falling accidents[2–5)]. Most slip and fall accidents in the workplace occur on wet (liquid-contaminated) floor surfaces[6–8)]. Floor surfaces in food factories and restaurant kitchens are often wet because of spilling water or oil, causing slips because of low friction due to the formation of a fluid film at the contact interface between the shoe sole and the floor surface. Therefore, a footwear pattern with high slip resistance on wet floor surfaces is required.

The coefficient of friction (COF) between the footwear and the underfoot surface is widely used as a measure of slip resistance. High static and dynamic coefficeint of friction (SCOF and DCOF, respectively) values are needed at the shoe-floor interface while walking to prevent slip initiation and to stop a slip if it occurs. Biomechanical studies on the safety limits of SCOF and DCOF[9–14)] indicate that SCOF and DCOF values of >0.4 are required at the shoe-floor interface to continue level walking without a slip and fall.

Surface pattern designs of footwear soles, 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., COF[6, 15–19)]. However, design criteria for a shoe sole pattern with a sufficiently high SCOF and DCOF on wet surfaces are unclear.

Yamaguchi *et al.*[20)] found that a rectangular rubber block with a rough surface has high SCOF and low DCOF

*To whom correspondence should be addressed.
E-mail: yamatake@gdl.mech.tohoku.ac.jp

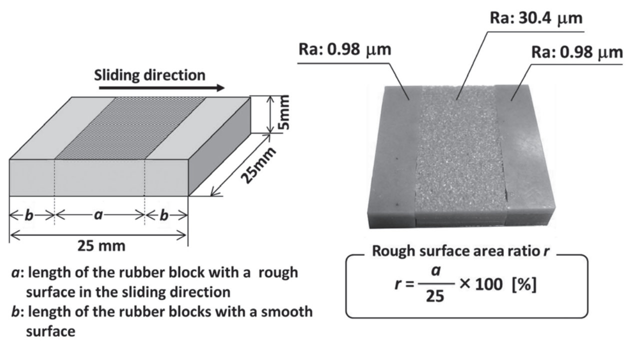


Fig. 1. Rubber block with a hybrid rubber surface pattern.

values, whereas a rubber block with a smooth surface has low SCOF and high DCOF values on a smooth stainless steel surface wet with glycerol solution. Based on this finding, they developed a rubber block with a surface pattern of rough and smooth surfaces (hybrid rubber surface pattern), as shown in Fig. 1. They demonstrated that the hybrid rubber block with a rough surface area ratio (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 of >0.4 on a wet surface. Superior slip resistance of the hybrid rubber surface pattern was achieved by dissipating the liquid film from the contact interface, resulting in a sufficient contact area between the rubber block and the mating surfaces at slip initiation (corresponding to SCOF) and while sliding (corresponding to DCOF)[20]. 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 on wet surfaces.

A new footwear outsole with a hybrid rubber surface pattern was prepared and tested in the present study to determine its efficacy for increasing slip resistance and reducing the risk of fall due to a slip while walking on a wet floor surface. We hypothesized that the footwear outsole with the hybrid rubber surface pattern would demonstrate higher SCOF and DCOF values on a wet floor than the outsoles of the conventional footwear used in food factories and restaurant kitchens. We also hypothesized that the footwear outsole would reduce slip occurence and prevent falling.

Methods

Test footwear

Figure 2 shows the test footwear. Footwear A (Fig. 2a) and B (Fig. 2b) were commercially available and are conventionally used in food factories and restaurant kitchens.

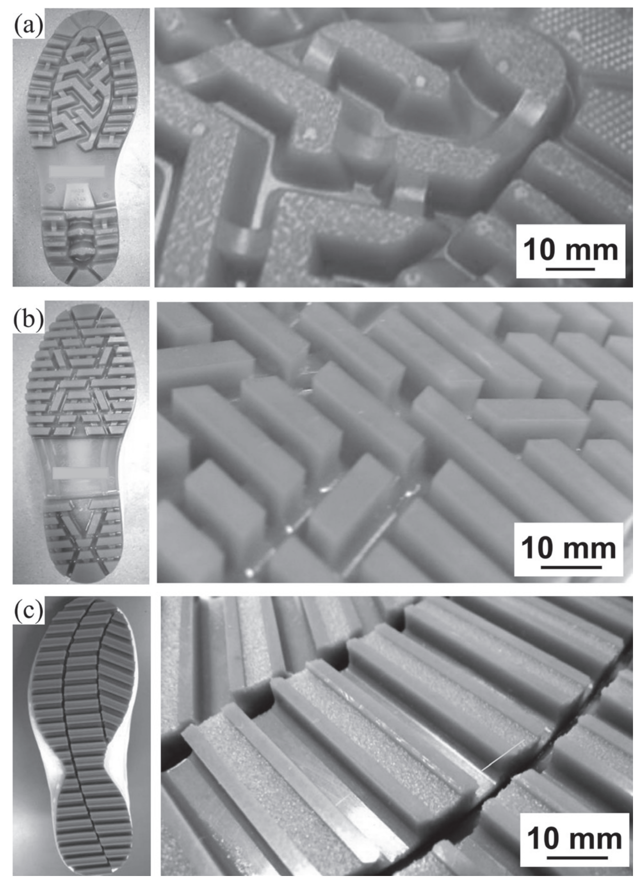


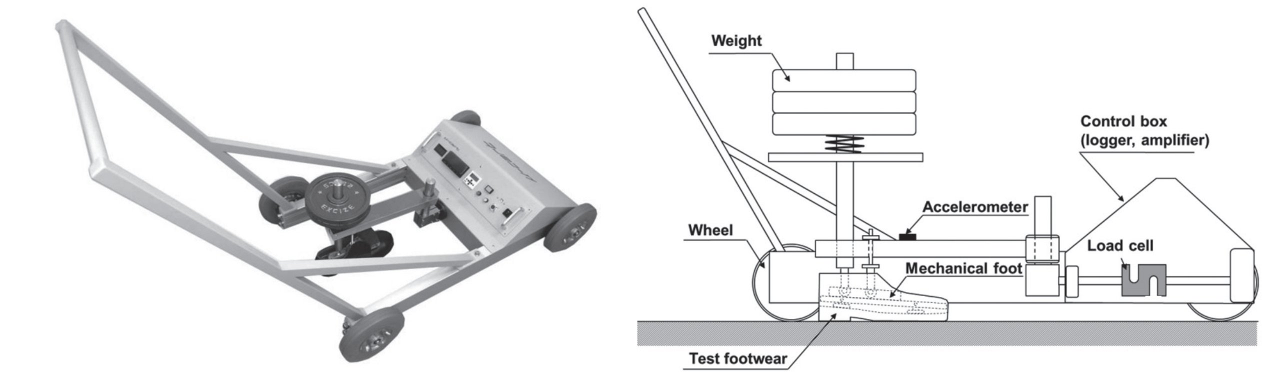
Fig. 2. Test footwear. (a) footwear A; (b) footwear B; (c) footwear C (with an outsole containing tread blocks with a hybrid rubber surface pattern).

Footwear C had an outsole with tread blocks (height: 3.5 mm, width: 9 mm) and a hybrid rubber surface pattern (Fig. 2c) and was manufactured for this study. The rough surface area ratio was 50% for the outsole with the hybrid rubber surface pattern. Comparative footwear A (Fig. 2a) had tread blocks (height: 4–7 mm) with a pearskin finish surface and a round chamfered edge, while footwear B (Fig. 2b) had tread blocks (height: 7 mm, width: 5 mm) with a smooth surface and a right edge. The outsole of all types of footwear was made from nitrile butadiene rubber [shore hardness: 53 (A/15) for footwear A; 55 (A/15) for footwear B; and 41 (A/15) for footwear C].

Drag test

A drag test was used to measure the relative slipperiness of each footwear type with respect to a wet stainless steel floor surface for testing our first hypothesis.

1. Experimental apparatus: A cart-type friction testing system for measuring SCOF and DCOF values for the shoe-floor interface (Fig. 3: μ-CART; Trinity-Lab Inc.,



(a) (b)

Fig. 3. (a) A cart-type friction testing system for measuring static and dynamic coefficient of friction (SCOF and DCOF, respectively) values for the shoe–floor interface and (b) schematic diagram of the configuration of the mechanical system (cross-sectional view).

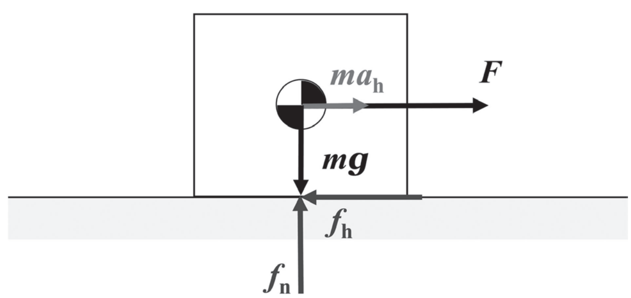


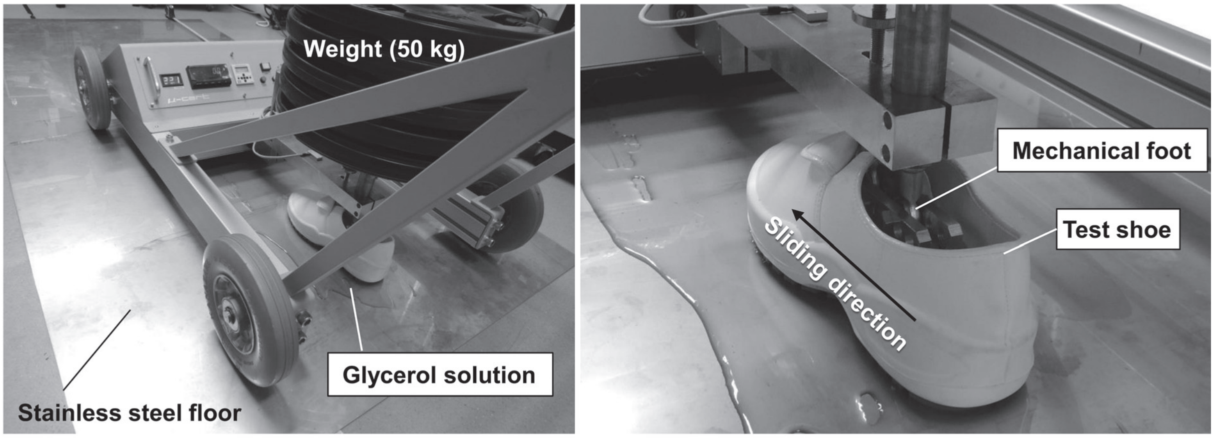
Fig. 4. Mechanical model for calculating the coefficient of friction (COF).

Tokyo, Japan)[21] was used for the drag test. The cart-type friction tester was pushed by the experimenter on the floor surface. The tested footwear was attached with a mechanical foot, and a normal load was applied to the footwear-floor interface with weights. The footwear was connected to a load cell, which measured the drag force, through the shaft and chassis. An accelerometer attached on the horizontal chassis or mechanical foot measured acceleration acting on the footwear. The force and acceleration data collected from the load cell and accelerometer (through an amplifier), respectively, were stored on a logger in the control box. If the sliding velocity of the footwear was constant during dragging, COF between the footwear and the floor surface was equivalent to the drag force, measured using the load cell, divided by the normal load. However, as the experimenter pushed the cart and the footwear was dragged on the floor surface, a variation in the sliding velocity of the footwear was unavoidable. Horizontal acceleration acting on the footwear during dragging was measured using the accelerometer mounted on the mechanical foot or chassis so that the inertia acting on the footwear could be compensated with respect to the drag force measured using the load cell. Based on the mechanical model presented in Fig. 4, COF between the shoe and the floor surface was calculated using the following formula:

$$COF = \frac{f_h}{f_n} = \frac{F - ma_h}{mg} \quad (1)$$

where f_h and f_n are friction force and normal load applied at the interface, respectively, F is the drag force measured using a load cell, m is the mass of the mechanical foot, footwear, and weights, a_h is the horizontal acceleration of the footwear measured using an accelerometer, and g is the gravitational force. The capacity of the load cell was 490 N, and the range of acceleration and the frequency response of the accelerometer were −6 to 6 G and DC–1,500 Hz, respectively.

2. Experimental condition: Fig. 5 shows the experimental set-up for the drag test. Three types of size 8 (26 cm) footwear were dragged using the cart-type friction tester on a stainless steel floor (2 m × 1 m × 2 mm), polished with a #400 abrasive paper. The floor was covered with glycerol solution (glycerin concentration: 70 wt%; viscosity: 19.7 mPa·s; Wako Pure Chemical Industries, Ltd., Osaka, Japan) using a spatula to ensure an even distribution of the solution before every test. The normal load was 514.5 N, which included the load of the weights (500 N), shaft, mechanical foot, and footwear. The cart was pushed, and the test footwear was dragged 1.0 m in approximately 2 s. The experimenter was asked to start dragging the footwear within 5 s after the weights were placed. The test



(a) (b)

Fig. 5. Experimental set-up for the drag test. (a) overview, (b) attaching part of the footwear.

was performed five times under identical conditions. The sampling frequency of the drag force and acceleration of the footwear was 1 kHz.

3. Data analysis: The drag force and acceleration data were low pass filtered (10 Hz). Then, COF was calculated using the above formula, and the sliding velocity of the test footwear v at the kth frame was calculated by numerical integration using the following formula:

$$v(k) = \sum_{i=1}^{k} \frac{(a_h(i-1) + a_h(i))\Delta t}{2} \qquad (2)$$

where i is the frame number and Δt is the sampling rate.

A representative time variation of COF and sliding velocity during the drag test is shown in Fig 6. SCOF was determined as the first peak of COF just before sliding onset. Mean SCOF and DCOF values at sliding velocities of 0.1, 0.2, 0.3, 0.4, and 0.5 m/s for five drag tests under identical condition were used for analysis.

Statistical analysis was performed using SPSS ver. 19.0 (SPSS, Inc., Chicago, IL, USA). One-way analysis of variance (ANOVA) was used to test if the SCOF values were affected by the footwear type. Post-hoc paired t-test with a Bonferroni correction were used to determine specific significant differences between footwear conditions. Two-way ANOVA was used to test if the DCOF values were affected by the footwear type and sliding velocity conditions. Post-hoc paired t-tests with a Bonferroni correction was used to determine specific significant differences between footwear or sliding velocity conditions. The significance level was set at p=0.05.

Gait trial

A repeated measures study was conducted with participants walking on the wet stainless steel floor surface while wearing the three types of footwear to test our second hypothesis.

1. Subjects: The study included 14 healthy adult males with an average age of 23.0 yr (range: 21–25 yr). Mean ± SD height and weight values of the subjects were 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.

2. Experimental procedure: Fig. 7 is a schematic representation of the experimental set-up. The stainless steel floor used in the drag test was mounted on a walkway and was covered with glycerol solution (glycerol concentration: 70 wt%) using a spatula to ensure an even distribution of the solution between trial blocks. 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 of the footwear.

Subjects were asked to walk straight, turn 180° at the end of the stainless steel floor, and return to the starting position, as shown in Fig. 8. They were instructed to walk at a self-selected pace and to do whatever came naturally to prevent a fall. The subjects wore a safety harness to help their balance, which was designed to prevent impact with the floor without otherwise restricting movement. The subjects were tested with the three types of footwear during separate sessions. The order of testing footwear conditions

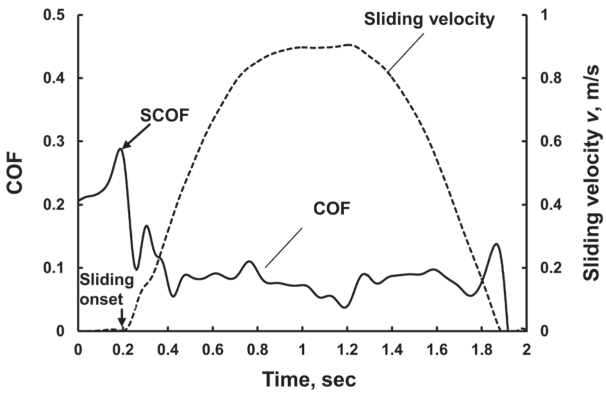


Fig. 6. Representative time variation in the coefficient of friction (COF) and sliding velocity; test footwear: footwear A, sliding velocity was calculated by numerically integrating the horizontal acceleration of the footwear.

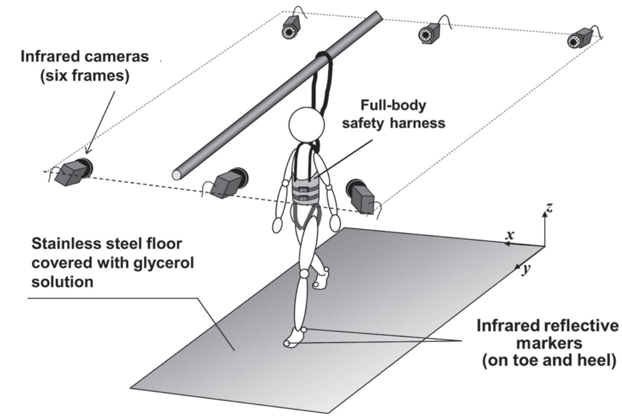


Fig. 7. Schematic of the experimental set-up for the gait trial.

was randomized to eliminate the effect of testing order on the results. Each trial was replicated three times under the same conditions (i.e., nine trials per subject), and all trials were videotaped.

3. Data analysis: 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 because of a slip. Whether the subjects fell was determined by 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 for trials in which it was difficult to identify a fall from the video data.

The heel horizontal velocity was calculated using the following formula:

$$v(i) = 60\sqrt{\left(\mathrm{x}_{\mathrm{heel}}(i) - \mathrm{x}_{\mathrm{heel}}(i-1)\right)^2 + \left(\mathrm{y}_{\mathrm{heel}}(i) - \mathrm{y}_{\mathrm{heel}}(i-1)\right)^2} \quad (3)$$

where, i is the frame number. The heel horizontal displacement from foot strike was calculated using the following formula:

$$D = \sqrt{\left(x_{heel}(n) - x_{heel}(m)\right)^2 + \left(y_{heel}(n) - y_{heel}(m)\right)^2} \quad (4)$$

where, $x_{\mathrm{heel}}(m)$ and $y_{\mathrm{heel}}(m)$ are the coordinates of the heel markers in the x and y directions at foot strike, and $x_{\mathrm{heel}}(n)$ and $y_{\mathrm{heel}}(n)$ are the coordinates of the heel markers in the x and y directions when the heel horizontal velocity becomes 0 after foot strike. The coordinate data for the reflective markers were digitally smoothed using a two-order low-pass Butterworth filter with a cut-off frequency of 10 Hz. A macro-slip was considered to have occurred if the heel horizontal velocity failed to reach 0 within a 3.0-cm heel horizontal displacement after foot strike[13, 22]; a slip of 0–3.0 cm was defined as a micro-slip, which is generally undetected[22]. The foot strike was determined on the basis of the vertical heel marker position. The slip trial associated with a macro-slip was identified if the maximum slip distance, D_{max}, which is the highest value of the heel horizontal displacement among all steps in each trial, was >3.0 cm. The frequency of trial with macro-slips/fall for each subject–footwear condition was calculated as the ratio of the number of trials with macro-slips/fall to the number of trials for each condition (three times). Therefore, the frequency of trials with macro-slips/fall was 0% (0/3), 33% (1/3), 67% (2/3), or 100% (3/3) for each subject-footwear condition. D_{max} and the maximum slip velocity, v_{max}, which is the maximum horizontal velocity of the heel marker among all steps in each trial, were used to examine slip severity.

4. Statistical analysis: Statistical analysis was performed using SPSS ver. 19.0. One-way repeated measures ANOVA was performed using the frequency of trial with macro-slips, frequency of trial with a fall, D_{max}, and v_{max} as dependent variables, and the footwear type as independent variables. Post-hoc paired t-tests with a Bonferroni correction were used to determine the specific significant difference. A significance level of 0.05 was used for these analyses. When appropriate, the frequency data were rank-transformed to ensure that the assumptions associated with ANOVA were adhered.

Results

SCOF and DCOF values during the drag test

Figure 9 shows mean SCOF values (Fig. 9a) and mean DCOF values as a function of sliding velocity (Fig. 9b) for

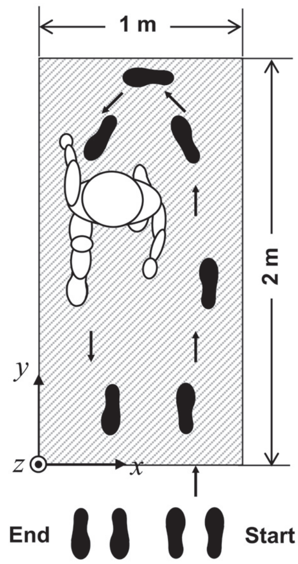


Fig. 8. Schematic of the 180° turn after walking straight on the stainless steel floor.

the three types of footwear. Error bars indicate SD.

One-way ANOVA indicated that the mean SCOF values were significantly affected by the footwear type ($p<0.001$); post-hoc analysis demonstrated that footwear C showed higher SCOF values than footwear A and B ($p<0.001$), but no significant differences were observed in the SCOF values for footwear A or B ($p>0.05$).

Two-way ANOVA indicated that the mean DCOF values were significantly affected by the footwear type ($p<0.001$), sliding velocity condition ($p<0.001$), and footwear-sliding velocity interaction ($p<0.001$). Post-hoc analysis revealed that footwear C showed higher DCOF values at all sliding velocity conditions (0.1–0.5 m/s) than footwear A and B ($p<0.001$). In addition, DCOF values for footwear A and C did not depend on the sliding velocity ($p>0.05$), whereas the mean DCOF value at 0.1 m/s was lower than that at other sliding velocity conditions for footwear B ($p<0.001$). Footwear B also showed higher mean DCOF values than footwear A at sliding velocities of >0.2 m/s ($p<0.01$). As shown in Fig. 9a and 9b, footwear C showed the mean SCOF values of ≥0.44 and the mean DCOF value of ≥0.39, which would be sufficient to continue level walking without slipping and falling based on the safety limits of SCOF and DCOF values[9–14].

Slip and fall frequency during the gait trial

Table 1 presents the mean frequency of trial with macro-slips and fall for each footwear type. The mean values of the frequency of trial with macro-slips for footwear A, B, and C were 95.2% (40/42), 26.2% (11/42), and 2.4% (1/42), respectively. One-way repeated measures ANOVA indicated that the footwear type significantly affected the frequency of trial with macro-slips ($p<0.001$); post-hoc analysis revealed that wearing footwear C (hybrid rubber surface pattern) significantly reduced the frequency of trial with macro-slips by 92.8 points and 23.8 points compared with wearing footwear A and B, respectively. The frequency of trial with fall while wearing footwear A was 54.0% (23/42), whereas no subjects fell while wearing footwear B and C.

Figure 10a and 10b shows the mean maximum slip distance (D_{max}) and slip velocity (v_{max}) for all types of footwear. Error bars indicate SDs. One-way repeated measures ANOVA indicated that the slip distance was significantly affected by the footwear type ($p<0.001$). Post-hoc analysis suggested that the mean D_{max} value for footwear C (0.01 ± 0.009 m) was significantly shorter than that for footwear A (0.32 ± 0.16 m, $p<0.001$) and footwear B (0.02 ± 0.015 m, $p<0.005$), as shown in Fig. 10a. One-way repeated measures ANOVA indicated that the slip velocity was significantly affected by the footwear type ($p<0.001$). Post-hoc analysis indicated that the mean v_{max} value for footwear C (0.18 ± 0.17 m/s) was the lowest among the three types of footwear (1.9 ± 0.9 m/s for footwear A; 0.43 ± 0.3 m/s for footwear B). In particular, the mean slip distance for footwear C was 9.6 mm, which was negligibly small. Slip distance and velocity are indicators of the risk of fall caused by an induced slip while walking, and greater slip distance and velocity are associated with a greater fall frequency[22–25]. Strandberg and Lanshammar[23] reported that the slip distance of >0.1 m and the slip velocity of >0.5 m/s result in a fall, and Brady *et al.*[24] suggested that the critical slip distance and velocity were 0.2 m and 1.1 m/s, respectively. The slip distance and velocity for footwear A (0.32 ± 0.16 m, 1.9 ± 0.9 m/s) were greater than those critical values of slip distance and velocity, thereby causing falls after slipping.

Discussion

The drag test findings indicate that footwear C with tread blocks and the hybrid rubber surface pattern showed higher SCOF (≥0.44) and DCOF (≥0.39) values than footwear A and B on a stainless steel surface wet with glycerol solution. These results support our first hypothesis. In addition, the hybrid rubber surface pattern outsole showed superior slip resistance and efficacy in reducing the risk of

Table 1. Frequency of trial with macro-slips and fall

	Footwear A (conventional)	Footwear B (conventional)	Footwear C (hybrid pattern)
Frequency of trial with macro-slips, %	95.2 ± 12.1	26.2 ± 19.3*	2.4 ± 8.9*,**
(number of trials with macro-slips)	(40/42)	(11/42)	(1/42)
Frequency of trial with a fall, %	54.0 ± 36.1	0	0
(number of trials with a fall)	(23/42)	(0/42)	(0/42)

* Significant difference to footwear A (p<0.01), ** Significant difference to footwear B (p<0.01)

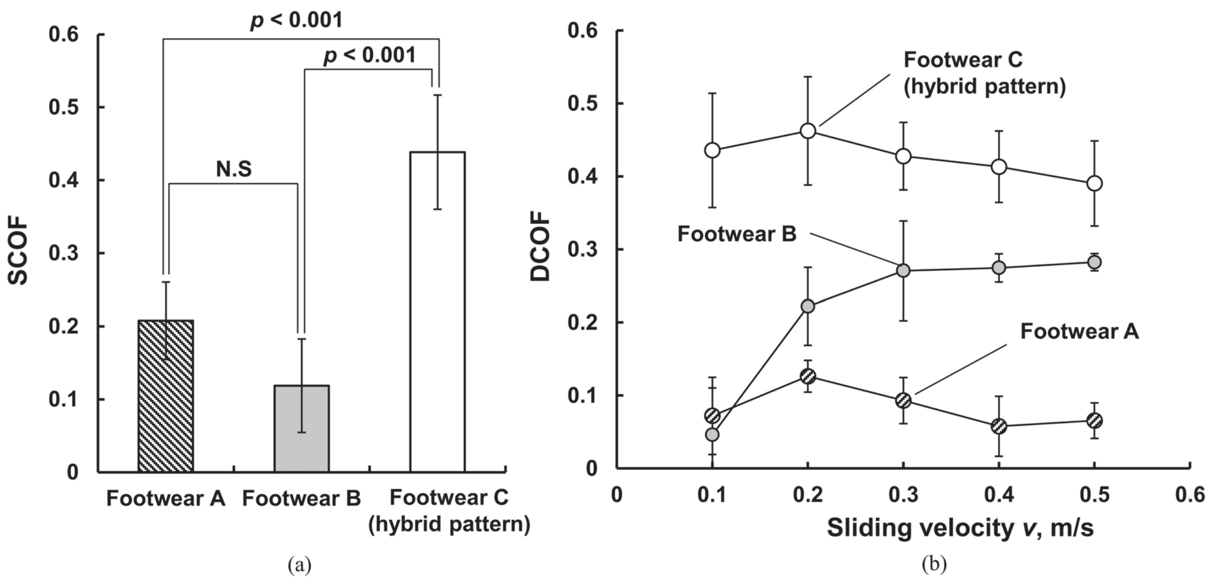


Fig. 9. Mean (a) static and (b) dynamic coefficient of friction (SCOF and DCOF, respectively) value as a function of the sliding velocity for each footwear type.

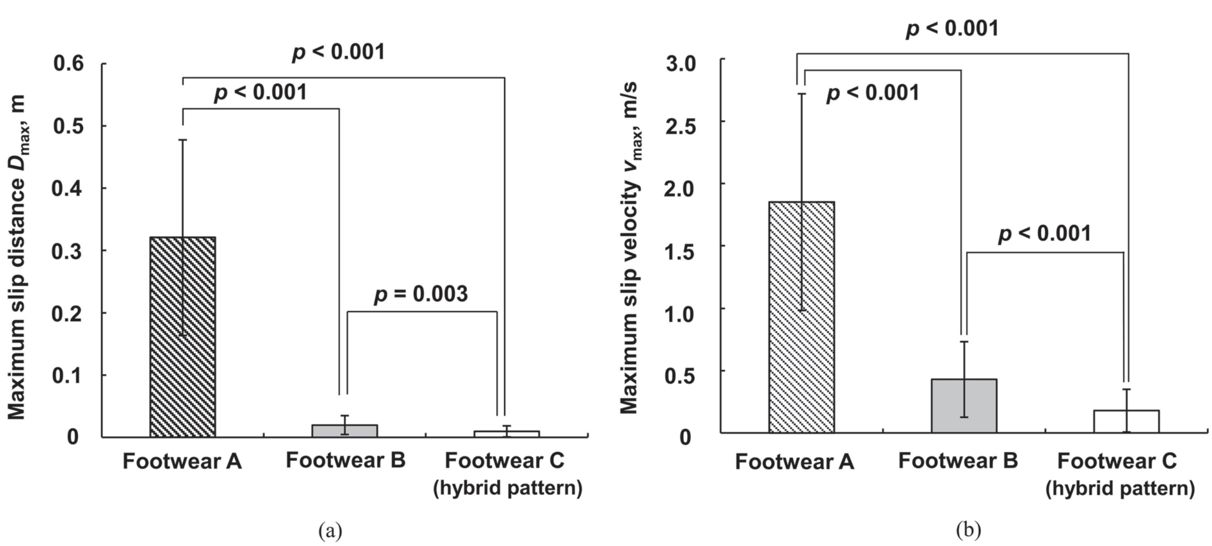
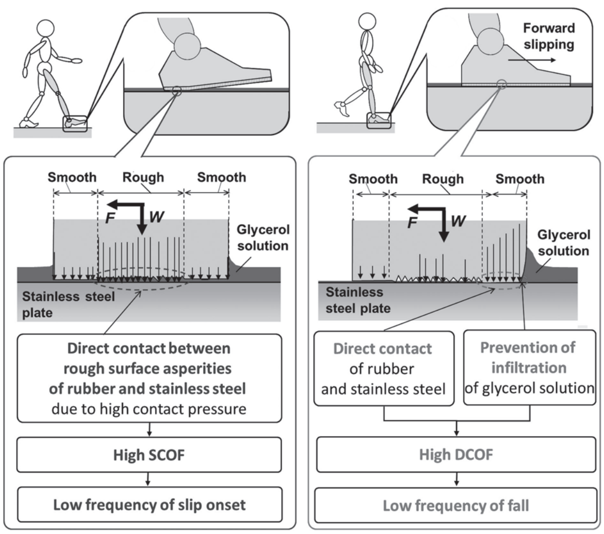


Fig. 10. Mean (a) slip distance and (b) slip velocity values for each footwear type.



(a) Before slip onset (b) During slipping

Fig. 11. Possible mechanisms for the low frequency of slips and falls using the footwear outsole with a hybrid rubber surface pattern.

fall during walking on a wet surface than the soles of the other footwear, which supports our second hypothesis.

As shown in Fig. 11a, when the tread block with the hybrid rubber surface pattern contacted the floor covered with glycerol solution, the glycerol film was removed from the contact interface 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 stainless steel floor surface. Thus, SCOF reached a high value, resulting in a low frequency of slip onset.

Even when a slip occurs because of a large traction caused by gait characteristics such as large step length[26, 27], the anterior right edge of the smooth surface component prevents infiltration of glycerol solution into the contact interface and deformation of the tread block increases the contact pressure at the anterior part of the block[28], which allows the smooth surface part to contact directly with the stainless steel surface (Fig. 11b). Therefore, DCOF reached a high value, resulting in a shorter slip distance (<3.0 cm) and low slip velocity.

In contrast, footwear A had tread blocks with a pearskin finish surface and rounded surface asperities. Therefore, the contact pressure between the asperities and the mating stainless steel floor surface was not high enough to remove the glycerol film from the contact interface when the tread block contacted the floor surface and during sliding, which resulted in a low SCOF value at slip initiation and a low DCOF value during sliding. Thus, slip and fall were more likely to occur in those wearing footwear A than those wearing footwear C. A liquid film remained at the contact interface when the footwear B outsole, which had tread blocks with a smooth surface and a right edge, contacted the floor surface because of a low contact pressure, resulting in a lower SCOF value and higher slip frequency than the footwear C outsole. However, after slipping, the contact area between the anterior part of the tread block and the floor surface increased while wearing footwear B, which resulted in a higher DCOF value than that while wearing footwear A. This high DCOF value resulted in a short slip distance and a low slip velocity, thereby resulting in no fall while wearing footwear B.

The difference in the slip distance and velocity between footwear B and C was because of the difference in the hardness of the rubber and the number of tread blocks. The hardness of the rubber sole of footwear C was lower than that of footwear B. Therefore, the deformation of tread blocks on footwear C would be higher than that on footwear B, which resulted in a higher contact pressure at the anterior part of each tread block[28]. Thus, the effect of the infiltration and removal of the solution film into and from the contact interface between the tread blocks and mating surfaces was more significant with footwear C than with footwear B. Footwear C had more tread blocks than footwear B; footwear B had no tread blocks at the planter arch part. Therefore, the resulting contact area between the tread blocks and the mating steel surface was larger while wearing footwear C, which would increase slip resistance.

A limitation of this study was that the experimental design of the gait trials did not eliminate the possibility of anticipating and adapting for a slip. The participants knew prior to the trial that they had to land and walk on a wet surface, and this may have led to a change in their gait to decrease slip potential, as reported in the literature[29]. Further investigations including a comparison of the hybrid rubber surface pattern outsole with more types of footwear outsoles are needed to clarify the efficacy of the outsole for preventing slips and falls on wet surfaces.

Conclusions

Our drag test and gait trial results obtained on a stainless steel floor surface wet with glycerol solution indicated that the newly developed hybrid rubber surface pattern outsole showed higher slip resistance than the soles of two types of commercially available footwear conventionally used in food factories and restaurant kitchens. The hybrid rubber surface pattern outsole exhibited higher SCOF (≥0.44) and

DCOF (≥0.39) values on the drag test than the soles of the comparative footwear. Because of such high SCOF and DCOF values, slip frequency, distance, and velocity for the footwear with the hybrid rubber surface pattern outsole were significantly lower than those for the soles of the comparative footwear, which resulted in no falls during trials. This study provides new information about footwear outsole pattern design and indicates that the newly developed footwear outsole will contribute to prevent slip and fall accidents in the workplace.

Acknowledgements

The authors would like to thank Kohshin Rubber Co., Ltd. for preparing and providing the footwear. The authors gratefully acknowledge Trinity-Lab Inc. for assisting with the drag test. The authors would also like to thank Dr. Hiroshi Onodera at National Nishitaga Hospital for great help with the trials and for valuable comments and suggestions.

References

1) Kawajiri Y, Suzuki Y, Nagata H (2001) Ergonomics studies on analyzing the risk of accidental falls in high-rise construction works. Specific research reports of the National Institute of Industrial Safety **22**, 1–5.
2) Japan Ministry of Health Labour and Welfare. Trends in deaths and death rates (per 100,000 population) from accidents by external causes: Japan: in Final data of general mortality 2012, Vital statistics of Japan. http://www.e-stat.go.jp/SG1/estat/ListE.do?lid=000001108739/emc300000-1.csv. Accessed May 7, 2014.
3) Nordin M, Andersson G, Pope M (1997) Musculoskeletal disorders in the workplace: Principles and Practice, 1st Ed., 152–166, Mosby, St. Louis.
4) Courtney TK, Sorock GS, Manning DP, Collins JW, Holbein-Jenny MA (2001) Occupational slip, trip, and fall-related injuries—can the contribution of slipperiness be isolated? Ergonomics **44**, 1118–37. [CrossRef]
5) Nagata H, Kim IJ (2009) Fall accidents in Japan and the classification of fall-risk factors. Proceedings of the International Conference on Slips, Trips, and Falls 2007–From Research to Practice, Hopkinton, 108–112.
6) Grönqvist R (1995) Mechanisms of friction and assessment of slip resistance of new and used footwear soles on contaminated floors. Ergonomics **38**, 224–41. [CrossRef]
7) Leclercq S, Tisserand M, Saulnier H (1995) Tribological concepts involved in slipping accidents analysis. Ergonomics **38**, 197–208. [CrossRef]
8) Manning DP, Jones C (2001) The effect of roughness, floor polish, water, oil and ice on underfoot friction: current safety footwear solings are less slip resistant than microcellular polyurethane. Appl Ergon **32**, 185–96. [Medline] [CrossRef]
9) Grönqvist R, Roine J, Järvinen E, Korhonen E (1989) An apparatus and a method for determining the slip resistance of shoes and floors by simulation of human foot motions. Ergonomics **32**, 979–95. [Medline] [CrossRef]
10) Grönqvist R, Hirvonen M, Rajamäki E, Matz S (2003) The validity and reliability of a portable slip meter for determining floor slipperiness during simulated heel strike. Accid Anal Prev **35**, 211–25. [Medline] [CrossRef]
11) Redfern MS, Bidanda B (1994) Slip resistance of the shoe–floor interface under biomechanically-relevant conditions. Ergonomics **37**, 511–24. [CrossRef]
12) Strandberg L (1983) On accident analysis and slip-resistance measurement. Ergonomics **26**, 11–32. [Medline] [CrossRef]
13) Fong DTP, Hong Y, Li JX (2009) Human walks carefully when the ground dynamic coefficient of friction drops below 0.41. Saf Sci **47**, 1429–33. [CrossRef]
14) Nagata H, Watanabe H, Inoue Y, Kim IJ (2009) Fall and validities of various methods to measure frictional properties of slippery floors covered with soapsuds, Proceedings of the 17th World Congress on Ergonomics, Beijing, CD-ROM.
15) Grönqvist R, Hirvonen M, Tohv A (1999) Evaluation of three portable floor slipperiness testers. Int J Ind Ergon **25**, 85–95. [CrossRef]
16) Wilson M (1990) Development of SATRA slip test and tread pattern design guidelines. In: Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces, ASTM STP1103. Gray BE (Ed.), 113–123, American Society for Testing and Materials, Philadelphia.
17) Chang WR, Kim IJ, Manning DP, Bunterngchit Y (2001) The role of surface roughness in the measurement of slipperiness. Ergonomics **44**, 1200–16. [Medline] [CrossRef]
18) Li KW, Chen CJ (2004) The effect of shoe soling tread groove width on the coefficient of friction with different sole materials, floors, and contaminants. Appl Ergon **35**, 499–507. [Medline] [CrossRef]
19) Li KW, Chen CJ (2005) Effects of tread groove orientation and width of the footwear pads on measured friction coefficients. Saf Sci **43**, 391–405. [CrossRef]
20) Yamaguchi T, Umetsu T, Ishizuka Y, Kasuga K, Ito T, Ishizawa S, Hokkirigawa K (2012) Development of new footwear sole surface pattern for prevention of slip-related falls. Saf Sci **50**, 986–94. [CrossRef]
21) Nomura S, Nomura T, Hokkirigawa K, Yamaguchi T, Shibata K (2014) Development of mobile measurement system of static and kinetic friction coefficient for shoe-floor interface, Proceedings of the Japanese Society of Tribologists, Tribology Conference, May 19–21, Tokyo, A22 (in Japanese).

22) Maynard WS (2002) Tribology: preventing slips and falls in the workplace. Occup Health Saf **71**, 134–40. [Medline]
23) Strandberg L, Lanshammar H (1981) The dynamics of slipping accidents. J Occup Accid **3**, 153–62. [CrossRef]
24) Brady RA, Pavol MJ, Owings TM, Grabiner MD (2000) Foot displacement but not velocity predicts the outcome of a slip induced in young subjects while walking. J Biomech **33**, 803–8. [Medline] [CrossRef]
25) Cham R, Redfern M (2002) Heel contact dynamics during slip events on level and inclined surfaces. Saf Sci **40**, 559–76. [CrossRef]
26) Yamaguchi T, Hokkirigawa K (2008) "Walking-mode maps" based on slip/non-slip criteria. Ind Health **46**, 23–31. [Medline] [CrossRef]
27) Yamaguchi T, Hatanaka S, Hokkirigawa K (2008) Effect of step length and walking speed on traction coefficient and slip between shoe sole and walkway. Tribol Online **3**, 59–64. [CrossRef]
28) Besdo D, Heimann B, Klüppel M, Kröger M, Wriggers P, Nackenhorst U (2010) Elastomere Friction, Theory, Experiment and Simulation, 188, Spinger, Germany.
29) Cham R, Redfern MS (2002) Changes in gait when anticipating slippery floors. Gait Posture **15**, 159–71. [Medline] [CrossRef]