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The Influence of Footwear Sole Hardness on Slip Initiation in Young Adults*

ABSTRACT: Slips occur when the friction demand of an individual exceeds the friction available from the shoe/floor interface. Shoe sole hardness is one of the factors thought to influence friction demand and available friction. The purpose of this study was to determine the influence of footwear sole hardness on the probability of slip initiation. Forty young adults were randomized into a hard or soft sole group. Slip events during the slippery floor trials were documented using a motion analysis system. The proportion of slip events in the hard sole group was greater than that in the soft sole group. The difference between utilized and available friction accurately predicted 90% of slip outcomes. Our data support the premise that individuals wearing shoes with harder soles are at greater risk for slipping. The results of this study suggest that shoe sole hardness should be considered when designing footwear aimed at decreasing slip risk.

KEYWORDS: forensic science, footwear, slips and falls, friction

Slips and falls are one of the most frequent causes of occupational accidents (1–6) and are associated with high rates of injury, disability, and death in the workplace (7,8). Slip and fall events involve a complex interaction of both extrinsic (environmental) and intrinsic (human) factors (9–13). Human factors thought to contribute to slip events include walking characteristics, anatomical/physical parameters, neurophysiological capacities, and the type of task being performed. Environmental factors include floor surface properties (i.e., material, roughness, and temperature), contaminants (i.e., nature of contaminant, viscosity of fluid contaminant, and depth of fluid film), and footwear characteristics (i.e., tread design, heel geometry, sole material and hardness).

During walking, slips occur when the friction demand (i.e., required or utilized friction) of an individual exceeds the friction available from the shoe/floor interface (14,15). With respect to shoes, sole hardness is one factor thought to influence shoe slip resistance. For example, harder soled shoes have been shown to provide less available friction than soft soled shoes (16–20). A decrease in the available friction would imply that persons wearing harder soled shoes could be at greater risk for slipping. However, previous studies have demonstrated that individuals reduce their friction demand when wearing hard soled shoes (21,22). Whether or not the observed decrease in friction demand when wearing hard soled shoes is enough to minimize or prevent slip risk has not been determined.

The primary purpose of this study was to investigate the effects of footwear sole hardness on the probability of slip initiation. It was hypothesized that persons who wear harder soled shoes would demonstrate a greater incidence of slip events compared to those who wear softer soled shoes. The secondary purpose of this study was to investigate the relationship between available friction (as measured using a footwear slip resistance tester) and peak utilized coefficient of friction (as measured from a force plate) on the probability of slip initiation. Information provided by this study is important to better understand the factors that may influence slip potential and for the design of footwear aimed at reducing slip risk.

Methods

Subjects

Forty healthy young adults between the ages of 23 and 40 years participated in this study. Subjects were randomized into one of two shoe groups: soft sole hardness ($N = 20$) and hard sole hardness ($N = 20$) (Table 1). Each group consisted of 10 males and 10 females. Subjects were recruited from the student population at the University of Southern California and the surrounding community. Prior to participation, each subject was fully informed as to the purpose of the study, procedures, and risks. Each signed an informed consent approved by the Institutional Review Board of the University of Southern California Health Science Campus. Subjects with any neurological or orthopedic conditions that would interfere with gait were excluded from the study. Furthermore, subjects with recent back injuries, lower extremity fractures, muscle strains, joint sprains, or who were potentially pregnant were excluded.

Instrumentation

Three-dimensional kinematics were obtained using an eight-camera motion analysis system (Vicon 612, Vicon Motion Systems, Lake Forest, CA). Kinematic data were sampled at 120 Hz. A reflective marker (25 mm sphere) attached to the heel was used to determine whether a slip had occurred.

Ground reaction forces were recorded using the force platforms (Model OR6-6-1000; Advanced Mechanical Technology, Inc., Watertown, MA). The force platforms were covered with smooth vinyl composition tile (similar to the laboratory floor) and aligned in the middle of a 10-m walkway. Analog force plate data were

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TABLE 1—*Group characteristics (N = 40); mean (standard deviation).*

	Hard shoe group (N = 20)	Soft shoe group (N = 20)	p-value*
Age (years)	27.1 (4.6)	27.8 (4.3)	0.62
Height (cm)	168.0 (7.1)	168.3 (9.4)	0.91
Weight (kg)	64.0 (10.8)	65.3 (10.7)	0.70

*Independent t-tests.

collected at 1560 Hz and converted to digital signals using a 16-bit analog to digital converter (Vicon Motion Systems).

Two sets of commercially available Oxford style dress shoes (Bates Footwear Inc., Rockford, MI) that differed only in outsole hardness were used in this study (Fig. 1). The material and appearance of the uppers of two pairs were identical, and the outsole of each pair was made from Styrene Butadiene Rubber. The outsole hardness was determined by American Society of Testing and Materials standard test method D2240-04 (ASTM Test Method for Rubber Property-Durometer Hardness). One set of shoes had a sole hardness of Shore 75A and was used for the soft shoe group testing, while the other set of shoes had a sole hardness of Shore 54D and was used for the hard shoe group testing. The outsoles of both sets of shoes were smooth with no tread pattern.

Two different floor surfaces were used in this study. A nonslippery, high pressure laminate was used to assess the utilized coefficient of friction (COFu) during a normal gait condition, while a slippery surface consisting of dry Teflon was used to assess slip initiation probability. The available friction between the soft and hard shoe outsoles and the dry Teflon surface was 0.36 and 0.16 respectively as determined using the Shoes and Allied Trade Research Association Physical Test Method (SATRA PM144 slip resistance tester) (23,24). This method determines the dynamic coefficient of friction between the footwear outsole and a given floor surface under conditions that simulate heel strike.

To ensure safety during all gait trials, subjects wore a fall-arresting safety harness (Miller Model 550-64; Miller Fall Protection, Inc., Franklin, PA) attached via a nonstretch lanyard (Miller Model FL11-1; Miller Fall Protection, Inc.) to an overhead trolley. The trolley moved along an overhead track (Fig. 2).

Procedures

All testing was performed in the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. Prior to the testing, subjects were fitted with the adjustable fall-arresting harness and shoes.

Subjects were tested under two conditions: (1) a normal nonslippery condition (dry high pressure laminate) and (2) a reduced available friction condition (dry Teflon). Subjects first performed multiple practice trials under the nonslippery condition in order to accommodate to the harness and trolley. After the accommodation period, a series of nonslip walking trials (nonslippery condition) were performed. In order to increase the friction demand, all subjects were instructed to ambulate at a fast walking speed. A walking trial was considered acceptable if the right foot fully contacted one of the three force plates without intentional targeting. Three nonslip walking trials were recorded. Following completion of the nonslip trials, a 60 cm by 120 cm dry Teflon panel was introduced into the walkway. Only one walking trial with the dry Teflon panel was obtained.

FIG. 1—*Pictures of the Oxford style shoes that were used in this study. Side view (left) and bottom view (right).*

FIG. 2—*During all walking trials, subject wore a fall-arresting safety harness attached via a nonstretch lanyard to an overhead trolley.*

As changes in gait characteristics because of an anticipation of the presence of a slip may occur (25,26), attempts were made to minimize these adaptations. Each subject wore a pair of appropriately tinted swimming goggles (Fig. 2), and was instructed to look at a spot on the wall at the far end of the walkway. Lights in the laboratory were lowered throughout all trials to reduce the chance of identifying the slippery surface. Between each trial (both nonslip walking and the slip-inducing trials), subjects waited outside of the laboratory for 1 min, which allowed the examiners sufficient time to change the floor surface panel for the reduced available friction condition. Subjects were kept outside of the testing laboratory for the same time period between both nonslip trials and prior to the slip-inducing trial. This prevented the subjects from knowing in which trial a slip was likely to occur.

Data Management and Analysis

The outcome of the reduced available friction trials was determined from the displacement of the heel marker. The presence of a slip was confirmed if the heel marker demonstrated forward horizontal displacement greater than 1 cm following initial contact.

To calculate the COFu during the nonslip walking trials, ground reaction force data were filtered at 350 Hz using low pass Butterworth fifth-order filter with zero lag compensation (DATAPAC 2K2 software; RUN Technologies, Mission Viejo, CA). Using Eq. (1), COFu was calculated as the ratio of the shear (algebraic resultant of the anterior–posterior and medial–lateral forces) to vertical ground reaction forces (GRFs) throughout the stance phase.

$$\mathrm{COF}\mu = \frac{\mathrm{ResultantShearGRF}}{\mathrm{VerticalGRF}} = \frac{\sqrt{(F_{\mathrm{Anterior-Posterior}})^2 + (F_{\mathrm{Medial-Lateral}})^2}}{F_{\mathrm{vertical}}} \quad (1)$$

The peak COFu during weight acceptance that would contribute to a forward foot slip was identified (Fig. 3). To avoid spuriously high values occurring when shear forces were divided by small vertical forces, only COFu data in which the vertical ground reaction force exceeded 50 N were analyzed (27). Initial contact was defined when the vertical ground reaction force exceeded 5 N.

The difference between utilized and available friction was calculated by subtracting the peak COFu of each subject from the available friction of shoe/floor interface (as measured from the SATRA test method). Therefore, the friction difference of each subject in the hard soled shoe group was 0.16 minus peak COFu, while the friction difference of each subject in the soft soled shoe group was 0.36 minus peak COFu. Using this convention, a positive friction difference value indicated that the available friction exceeded the peak COFu for a given subject. A negative friction difference value indicated that the peak COFu of the subject exceeded the available friction.

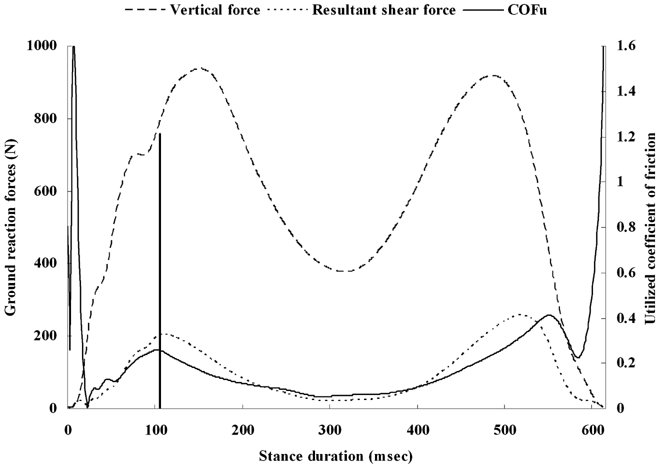

FIG. 3—*Representative tracings of COFu and ground reaction forces during the stance phase of walking. Note that the initial spuriously high spikes in COFu at the beginning and end of the stance are due to relatively low vertical ground reaction forces. The vertical line indicates point of peak COFu during weight acceptance and corresponding vertical and resultant shear forces.*

Statistical Analysis

A Fisher's exact test was used to assess group differences in the proportion of slip events during the reduced friction trials. The dichotomous-dependent variable was slip outcome (i.e., slip or no-slip). The independent variable was footwear sole hardness (i.e., hard or soft). In addition, independent *t*-tests were performed to determine the differences in peak COFu between the shoe hardness groups.

To determine the relationship, the friction difference between available friction and peak COFu, on the probability of slip initiation, a logistic regression model was generated. Significance was evaluated using a forward stepwise likelihood ratio (LR) test. The dependent variable (slip outcome) was coded as a binary variable with 1 equal to "slip" and 0 equal to "no-slip." All statistical tests were performed using SPSS 11.5 statistical software (SPSS, Inc., Chicago, IL). A two-sided significance level of 0.05 was used for all statistical analyses.

Results

On average, the self-selected fast walking speed of the hard and soft soled shoe groups was similar (1.9 ± 0.2 m/sec vs.1.9 ± 0.1 m/sec, $p = 0.41$; Table 2). The peak COFu was significantly lower in the hard soled shoe group compared to the soft soled group (0.24 ± 0.04 vs. 0.26 ± 0.04, $p = 0.05$; Table 2).

Seven of twenty subjects in the hard soled shoe group (35%) experienced a slip during the reduced available friction trial, while none of the subjects in the soft soled shoe group exhibited a slip event (Table 3). The proportion of slip events in the hard soled shoe group was statistically greater than the proportion of slip events in the soft soled shoe group (Fisher's exact test, $p = 0.008$).

The logistic regression analysis revealed that the friction difference between available friction and peak COFu was significantly associated with the probability of slip initiation (LR = 12.35 on 1 df, $p < 0.0001$). This logistic regression model overall correctly predicted 90% of the slip outcomes experienced by our subjects (Fig. 4). The model most accurately predicted when a slip did not occur (32 out of 33) and predicted 57.1% of the events when a slip did occur (4 out of 7). The logistic regression equation was formulated as logit probability (slip) = (−2.585) −24.589 × (friction difference).

TABLE 2—*Walking velocity and peak utilized coefficient of friction during weight acceptance; mean (standard deviation).*

	Hard Shoe Group (N = 20)	Soft Shoe Group (N = 20)	p-Value*
Velocity (m/sec)	1.9 (0.2)	1.9 (0.1)	0.41
Peak COFu†	0.24 (0.04)	0.26 (0.04)	0.05*

*Independent *t*-tests.
†Utilized coefficient of friction.

TABLE 3—*Slip proportions between groups, number of slips (% within group).*

	Slip	No-Slip	Total*
Hard shoe group	7 (35%)	13 (65%)	20
Soft shoe group	0 (0%)	20 (100%)	20

*Fisher's exact test, $p = 0.008$.

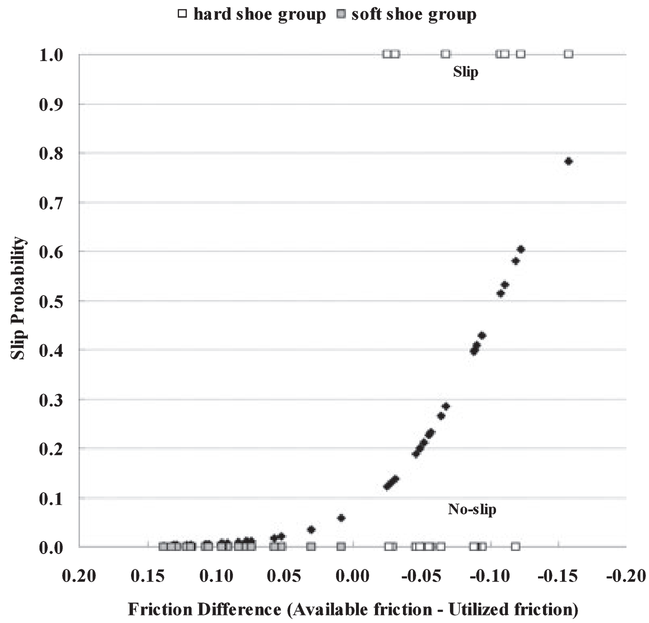

FIG. 4—*The logistic regression showing the relationship between predicted slip probability and the friction difference (available friction from shoe/floor interface—peak COFu of an individual). This model overall correctly predicted 90% of the slip outcome experienced by our subjects. Squares represent the observed data and diamonds represent the predicted data.*

Discussion

The results of current study support the hypothesis that persons wearing hard soled shoes are more likely to experience a slip event when compared to persons wearing soft soled shoes. This finding is consistent with the mechanical testing that was performed as part of this study which showed a substantial decrease in the available friction of the hard soled shoes compared to soft soled shoes (0.16 vs. 0.36). Such finding provides objective evidence supporting the link between footwear sole hardness and slip potential.

It has been reported that individuals decrease their friction demand when wearing harder soled shoes (21,22). In particular, Tsai and Powers in 2006 demonstrated that this decrease in friction demand was attributed to gait adaptations aimed at decreasing the resultant shear forces of the foot against the floor. A similar trend was found in the present study in that subjects in the hard sole group demonstrated a decrease in peak COFu when compared to the subjects in the soft sole group (0.24 vs. 0.26). Despite the lower friction demand, however, the available friction of the hard soled shoes was substantially less than the average COFu of the subjects in the hard shoe group (0.16 vs. 0.24). In contrast, the available friction of the soft soled shoes was greater than the average COFu of the subjects in the soft shoe group (0.36 vs. 0.26). Given as such, it was not surprising that a higher proportion of slip events occurred in the hard sole group.

Several authors have discussed the possible mechanisms by which footwear sole hardness can influence slip potential (12,28). Deformation of both the shoe and floor surface can contribute to the available friction of the shoe/floor interface (17,29,30). Material hardness, contact area, surface roughness, and the load applied, influence the deformation of the contacting materials. A sole material which is able to deform to increase the contact area with the floor surface has been suggested to provide greater slip resistance (14,31). Grönqvist et al. (30,32) have reported that the hardness of the heel material accounts for approximately 50% of the variance of the available friction.

TABLE 4—*Logistic regression model of predicting slip probability based on the friction difference.*

Probability of a Slip Occurring	Friction Difference*
0.01	0.08
0.05	0.02
0.50	−0.11
0.95	−0.23
0.99	−0.29

*Friction difference = (available friction from the shoe/floor interface—utilized coefficient of friction).

Using the logistic regression model generated as part of this study, slip probability was estimated based on the friction difference values (Table 4). These calculations revealed that there was 1% probability of a slip occurring when the available friction from shoe/floor interface exceeded the peak COFu by 0.08. There was 50% probability of a slip occurring when the available friction from shoe/floor interface was 0.11 less than the peak COFu. However, there was 99% probability of a slip occurring when the available friction from shoe/floor interface was 0.29 less than the peak COFu. These results suggest that a relatively small change in available friction from the shoe/floor interface owing to sole hardness may have a large influence on slip probability.

The logistic regression model also indicated that a slip event was predicted by the difference between available friction from shoe/floor interface and peak COFu. More specifically, the model overall correctly predicted 90% of the slip outcomes experienced by our subjects. This level of predictability is very close to that reported by Burnfield and Powers (15) who demonstrated that the relationship between peak COFu and the available friction correctly predicted 89.5% of slip events.

Despite the high overall predictability, however, the model only predicted 57.1% of actual slip events. There are several reasons for this modest level of predictability including the possibility that the available friction between the shoe/floor interface as measured from the SATRA footwear slip resistance tester may not represent the "true" available friction between the shoe/floor interface during ambulation. The SATRA test method utilizes a standard vertical force, impact velocity, and shoe angle to measure available friction; however, not all individuals walk in the same manner. Given as such, care must be taken in attributing any given SATRA measurement to a specific slip outcome.

The findings of the current study confirm existing assertions that footwear sole hardness is an important contributor to slip risk and should be considered when designing shoes aimed at reducing the incidence of slip events. In addition, our results have industrial implications as shoes are often made from harder materials in order to reduce abrasion over time. However, it is possible that the potential for decreased slip resistance might put individuals at risk for slip and fall injuries, especially in the presence of a contaminant or reduced friction situations.

One limitation in the current study is that none of the subjects have worn the hard soled shoes in their daily life. According to the questionnaire they filled out, most subjects wore sneakers, sport shoes, or flip-flops. It is possible that the risk of slip by persons who normally wear harder soled shoes may be considerably less than that presented in this study. Since the persons who normally wear harder soled shoes may have adapted to different gait patterns, that may further reduce their COFu. Footwear wearing habits of individuals needs to be considered in future research investigating human slips and falls.

Conclusion

Footwear sole hardness is an important factor with respect to slip probability. In particular, our data support the premise that individuals wearing shoes with harder soles are at greater risk for slipping. Future studies should consider other footwear characteristics (i.e., heel height, tread pattern, sole contact area) in relationship to slip potential, so that optimal slip-resistant footwear designs can be developed.

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