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## The Effect of Subject Awareness in Assessing the Probability of Slip and Fall Accidents

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Principal Investigator/Applicant  
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RS2001/02-028

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May 17, 2005

Research Secretariat  
Workers' Compensation Board of BC  
6951 Westminster Highway  
Richmond, BC  
V7C 1C6

Attention: Ms. Penny Lowe,

**Re: Final Report  
RS2001/02-028**

Attached please find the final report for our grant entitled "The Effect of Subject Awareness in Assessing the Probability of Slip and Fall Accidents." If you have any questions, please call me. Thank you for supporting this research.

Yours very truly,  
**MEa Forensic Engineers & Scientists Ltd**

Gunter Siegmund, PhD, PEng

## **MAIN RESEARCH FINDINGS**

- Tribometers (floor friction measuring devices) can be used to predict the risk of slipping on a particular floor surface. To predict slip risk, tribometers must first be calibrated against slip data generated by human subjects.
- Human subjects adapt their gait when they are aware the floor surface is potentially slippery and further adapt their gait after actually slipping on a particular floor surface. These adaptations can contaminate the human subject data needed to develop the slip risk curve for a tribometer.
- The risk of slipping decreases rapidly with multiple exposures to a slippery surface and with prior experience slipping on that surface.
- The gait adaptations of subjects who are aware they may slip but who have not yet slipped bias the slip risk curves for a tribometer and generate inaccurate predictions of slip risk.
- Despite the presence of large gait adaptations in subjects who are both aware of the potentially slippery surface and have recent slipping experience, these gait adaptations do not bias the slip risk curves.
- The results of this study indicate that tribometers used to measure floor slipperiness can be validated using data acquired from human subjects who have prior experience slipping in a laboratory. Compared to using subjects who slip only once, this finding significantly reduces the time and effort needed to validate a tribometer.

## **EXECUTIVE SUMMARY**

Prior knowledge of potentially slippery conditions has been shown to alter normal human gait in slip and fall experiments. We sought to quantify how the empirical relationship between slip probability and available floor friction was affected by subject awareness and prior slip experience. Sixty-eight subjects (40F, 28M) walked over three different low-friction surfaces inserted periodically between non-slip control trials. Three increasing levels of prior knowledge were used: deceived (unaware of the slippery surface), aware (20% chance of a slippery surface, but no prior slip experience), and experienced (aware with prior slip experience). Available friction was measured using a drag sled and a variable incidence tribometer. Of 620 low-friction trials, 124 generated slips greater than 27 mm. The proportion of slips, the slip distance and the required friction (taken from the control trial immediately before a low-friction trial) generally decreased with increasing levels of prior knowledge. These adaptations were accommodated by logistically regressing slip outcome (yes/no) against the normalized friction (available friction minus required friction) rather than against available friction alone. The regressions showed that subject awareness biased the slip probability curve toward a lower slip risk for a given normalized friction, but that the subsequent addition of slip experience generated a slip risk curve that was not significantly different from that of deceived (and presumably unprepared) subjects. These findings suggest that data to validate a tribometer's ability to predict the risk of slipping (but not falling) can be acquired from subjects with prior slip experience.

## **FINAL REPORT**

### **Research Problem/Context**

Slips and slip-related falls are responsible for many musculoskeletal injuries (Strandberg and Lanshammar 1981; Manning 1983) and are typically initiated when the friction at the shoe/floor interface is less than expected (Leamon and Son 1989; Tisserand 1985). The friction of a particular floor surface can be measured using a device called a tribometer, of which more than 50 different types exist (Strandberg and Lanshammar 1981). Although all tribometers are designed to measure friction, the values measured by different tribometers are often not the same – even when identical test feet, flooring materials and contaminants are used (Chang and Matz 2001; Marpet 1996; Marpet and Fleischer 1997; Powers et al 1999). As a result of this inter-tribometer variability, a tribometer's validity must be established before its measurements can be used to predict the probability of a slip on a particular surface.

Numerous studies have attempted to correlate the friction measured with a tribometer to the occurrence or severity of slips in ambulating human subjects (Perkins 1978; Myung et al 1992; Myung 1997; Hanson et al 1999; Kulakowski et al 1999; Brady et al 2000; Lockhart et al 2000a,b). Although these studies have shown that more slips and longer slips (more likely to lead to a fall) occur when floor friction is low, only one study used sufficient subjects, trials and friction conditions to establish an empirical relationship between tribometer measurements and the probability of slipping and falling (Hanson et al 1999). Unfortunately, the results of this latter study are difficult to apply outside the laboratory for three reasons. First, the tribometer used in the study is a research instrument and not available commercially. Second, most of the slip trials were acquired on a sloped surface and humans alter their normal gait on sloped surfaces (Redfern and DiPasquale 1997; McIntosh 2001). And finally, the subjects were aware of

the slippery surfaces and had prior experience slipping on these surfaces, two factors that generate anticipatory changes in gait and alter the probability of recovery after a slip (Cham and Redfern, 2001; You et al., 2001; Marigold and Patla, 2002; Heiden et al., in review).

The goal of this study was to quantify how the empirical relationship between slip probability and floor friction is affected by the awareness and prior slip experience of human subjects. To improve on previous work (Hanson et al 1999), floor friction was quantified using two commonly-available tribometers and all trials were conducted on a level floor surface. Given that human subjects adopt a more cautious gait when they are aware of a potentially slippery surface, we hypothesized that subjects who encountered a slippery floor unexpectedly would have a greater probability of slipping than either subjects who were aware of the slippery surface or subjects who had recent slip experience. The results of this study will help provide validation data for two common tribometers and will show whether experiments designed to validate tribometers need to control their experimental conditions or correct their data for subject awareness and experience.

### **Methodology**

Sixty-eight healthy subjects (40 females, 28 males) between 18 and 40 years old participated in this study. The females were  $25 \pm 6$  (mean  $\pm$  SD) years old,  $165 \pm 6$  cm tall and had a mass of  $61 \pm 12$  kg; the males were  $27 \pm 5$  years old,  $177 \pm 5$  cm tall and had a mass of  $77 \pm 8$  kg. Subjects reported no history of dizziness, vestibular dysfunction, neurological disorders, low-back pain or orthopaedic abnormalities of the lower extremities. All subjects read and signed an informed consent form approved by the university's Clinical Research Ethics Board.

### ***Instrumentation***

Ground reaction forces were measured using a force plate (Bertec 4060H, Columbus, OH) embedded near the middle of a 10m walkway. Force plate signals were low-pass filtered (1000Hz; 500Hz for the 4060 plate) before being sampled simultaneously using a 12-bit data acquisition system (Win30 DAQ, United Electronics Incorporated, Watertown, MA) at 2400 Hz for 6 seconds. Overhead harness loads were measured using a uni-axial load cell (Artech SS20210, Riverside, CA). Sagittal-plane motion of a heel marker on the left shoe was measured from video data acquired at 60 Hz (Sony Digital 8 DCR-TRV320).

### ***Slip apparatus***

The walkway was clad in vinyl composition tile over a concrete sub-floor. Subjects wore a safety harness tethered from each shoulder to an overhead trolley. Tether length was adjusted to minimize interference with normal walking and to prevent a subject's arms from reaching the floor in a fall.

Four levels of shoe/floor friction were achieved using 40x60cm sheets of paper placed on a 40x60cm polished aluminum plate mounted to the top of the force plate, level with the surrounding floor. The visible surface of all paper sheets was identical and consisted of 600 grit sandpaper to eliminate sliding between the shoe and paper. Glued to the back of the sandpaper were four materials: wax paper, office printer paper, nothing (the backing of the sandpaper was used) and aluminum foil. The latter material was used as the non-slip surface for normal walking trials; the three other surfaces represented a range of low friction surfaces for the slip trials.

### ***Test procedures***

Subjects wore appropriately-sized lace-up trainers with a polyurethane rubber sole (Nike 2530c Air Pegasus). A start position was selected to ensure the left limb struck the

force plate after at least five steps. Subjects were instructed to walk with a level gaze at their preferred speed and to not target the force plate. Normal light levels were used since it was not possible to discern the friction level from the outward appearance of the paper on the slip plate. A different paper sheet was used for every trial to prevent subjects from potentially identifying friction levels from blemishes or marks on the sandpaper surfaces.

All subjects completed 40 trials (4 blocks x 10 trials/block). Subjects accommodated to wearing the harness and walking over the high friction surface during the first block and measurements of their normal gait were made during the second block. Despite being told there would be no slips in the first two blocks, one of the three low friction surfaces (randomly selected) was inserted for the last trial of the second block. After this deception, subjects were told that two low friction surfaces (the same friction level experienced in their deception trial) would be inserted randomly in the third block. All subjects were then exposed once to each of the three low friction surfaces during the fourth block. The first 46 subjects also completed two additional blocks of 10 trials: one at a self-selected slow walking speed and the other at a self-selected fast walking speed. All three low-friction surfaces were presented once in each additional block. These trials were used to generate a broader range of walking data. The presentation order of the slow, normal and fast blocks (4<sup>th</sup>, 5<sup>th</sup> and 6<sup>th</sup> blocks) was randomized in these 46 subjects.

### ***Tribometer measurements***

Friction between the three low-friction paper sheets and the aluminum surface of the force plate was measured using two tribometers: a 15 kg drag sled (DS) designed in accordance with the National Standards of Canada CAN2-75.1-M77; and a variable incidence tribometer (VIT; English XL, William English Inc, Alva, FL). Each surface was tested with each tribometer 3 times per day for 13 days (n=39 tests per surface/tribometer combination). The force plate surface was cleaned prior to each

tribometer test (and each human subject test). The available friction measured by the DS was computed from the force plate data as the resultant horizontal force divided by the vertical force (Equation 1), whereas the friction measured by the VIT was read directly from the scale on the English XL. Both tribometers distinguished between the three surfaces and ranked them in the same order of slipperiness (Table 1).

$$\mu_{available} = \frac{\sqrt{F_x^2 + F_y^2}}{F_z} \quad (1)$$

Table 1. Mean (SD) of friction values measured for the three low-friction surfaces using the two tribometers.

Tribometer	Wax paper	Office paper	Sandpaper back
Drag sled (DS)	0.101 (0.011)	0.150 (0.035)	0.181 (0.039)
Variable incidence tribometer (VIT)	0.118 (0.013)	0.167 (0.020)	0.191 (0.017)

### **Analysis**

All low-friction trials were classified as either a fall, slip or non-slip trial. A fall occurred if the harness load reached 50% of body weight (Brady et al 2000). Slips and non-slips were differentiated using the forward displacement of the left heel marker after heel strike. The slip distance used to distinguish slips from non-slips was determined using a logistic regression of slip distance against the experimenter's (TLH) judgment of slip for each subject's deception trial. Since all of the non-slip trials (n=44) had heel displacements <23 mm and all of the slip trials (n=20) had heel displacements >32 mm, the slip distance (27 mm) associated with a 50% slip probability yielded positive and negative predictive values of 100%. Four deception trials were not included in this analysis because the slip limb did not land wholly on the paper.

To test for differences in the number of slips on each low-friction surface, chi-square tests for homogeneity were performed on the 3 x 2 (friction level x slip type) contingency tables. Post hoc analyses were then performed using simple 2 x 2 chi-square comparisons to identify differences between the surfaces. Differences in the number of slips generated on a specific surface across repeated exposures were assessed using a Cochran Q test. The omnibus chi-square analyses were evaluated non-directionally at a significance level of  $\alpha=0.05$ . The significance levels for the non-directional post-hoc chi-square tests were adjusted for the number of post-hoc comparisons using a Bonferroni adjustment. Post-hoc differences in the Cochran Q test were evaluated directionally (a decrease in slip rate was expected) using a modified Bonferroni-Dunn method ( $CD_c$ ) (Sheskin, 1997).

To develop the empirical relationships needed to predict the probability of slipping,  $P(\text{slip})$ , from a tribometer's measurement of friction, separate logistic regression analyses were performed using either available friction or normalized friction as the independent variable (Equations 2a and 2b respectively). Available friction was measured directly using the tribometer. Normalized friction was defined as the arithmetic difference between the available friction ( $\mu_{\text{available}}$ ) and the required friction ( $\mu_{\text{required}}$ ) (Hanson et al 1999). Required friction was defined as the friction required by an individual to walk over the surface without slipping and was taken from the high-friction trial immediately preceding a low-friction trial (whether or not a slip occurred during the low-friction trial). Required friction was computed from the force plate data (Figure 1) as the average friction over the 100 ms following slip limb heel strike in the non-slip trial.

$$P(\text{slip}) = \frac{\exp(b_0 + b_1 \mu_{\text{available}})}{1 + \exp(b_0 + b_1 \mu_{\text{available}})} \quad (2a)$$

$$P(\text{slip}) = \frac{\exp(b_0 + b_1(\mu_{\text{available}} - \mu_{\text{required}}))}{1 + \exp(b_0 + b_1(\mu_{\text{available}} - \mu_{\text{required}}))} \quad (2b)$$

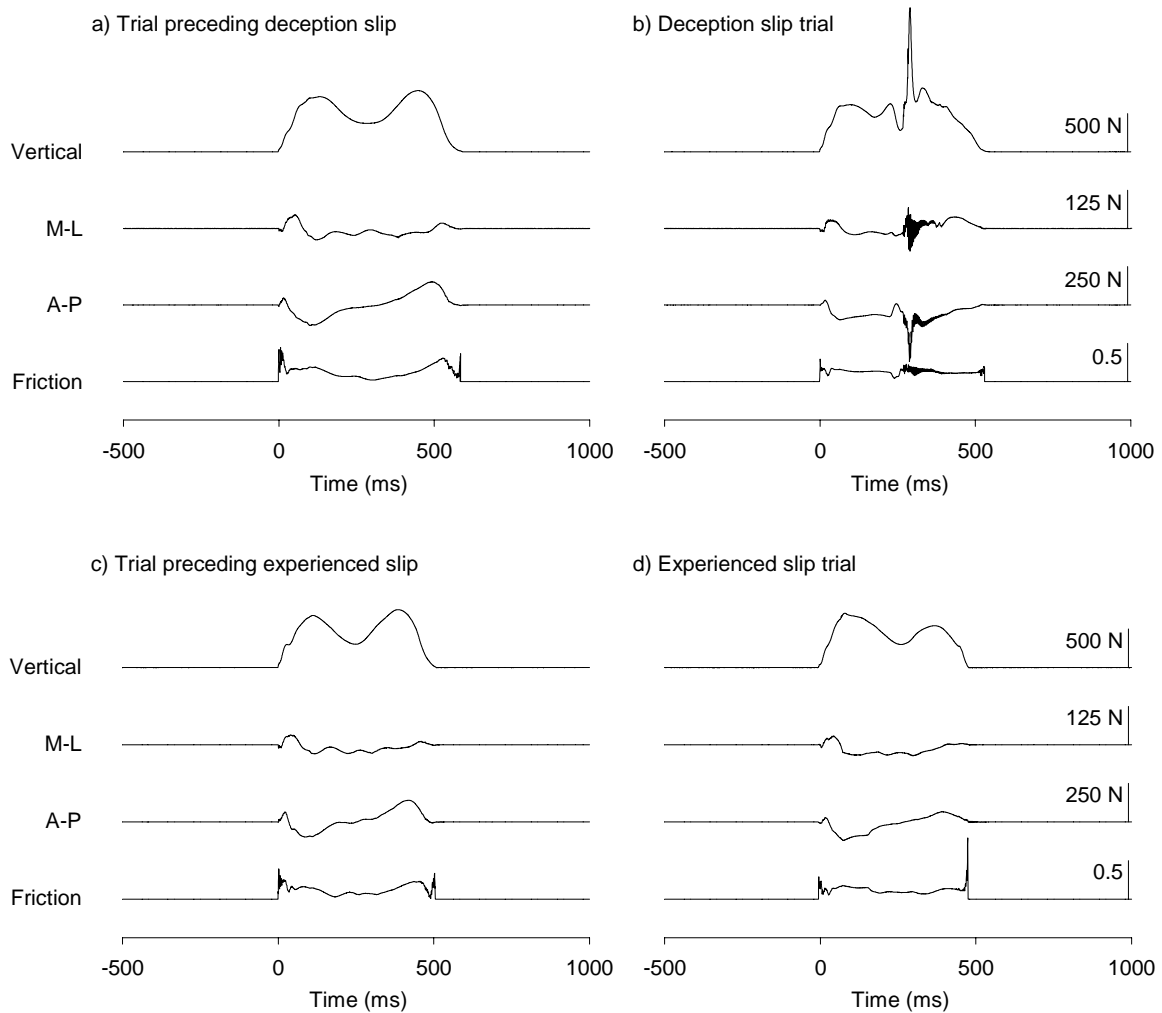


Figure 1. Sample ground reaction data for four trials: a, the trial preceding the deception slip trial; b, the deception slip trial; c, the trial preceding an experienced slip trial; and d, the slip trial with prior experience. All data from a single subject. Time  $t = 0$  ms at heel strike. Vertical force  $F_z$ ; M-L, mediolateral force  $F_y$ ; A-P, anterior- posterior force  $F_x$ ; Friction, utilized friction  $\mu$ .

For each tribometer, separate logistic regressions were computed using three groups of data: i) the deception (D) trials ( $n=64$ ), which were assumed to represent the probability of actual unexpected slips; ii) the aware (A) trials ( $n=195$ ), in which subjects

were aware the surface was potentially slippery but had no prior slip experience; and iii) the experienced (E) trials (n=361), in which subjects were both aware of a potentially slippery surface and had prior slip experience. Differences in the  $b_0$  and  $b_1$  coefficients between the three groups were evaluated using a Wald statistic if the residual variations were not significantly different between groups (Allison, 1999). If the residual variations were significantly different, a likelihood ratio test was performed to determine if at least one of the coefficients was different (Allison, 1999). Regression analyses were conducted using Statistica (v6.1, Statsoft, Tulsa, OK) and comparisons between coefficients were performed at the  $p < 0.05$  level. Confidence bands for the regressions were computed using variance-covariance matrices (Sofroniou and Hutcheson, 2002).

### **Research Findings**

Slips occurred in 31 (17%) of the 181 low friction trials in Blocks 2 and 3; no falls occurred in this study. Within these first three low friction trials, the wax paper surface generated proportionally more slips than the other two low-friction surfaces in the first and second exposures ( $p < 0.0036$ ), but not in the third exposure ( $p > 0.072$ ) (Figure 2a). The proportion of slips decreased between the first and second exposures to both the wax paper and sandpaper backing surfaces ( $p = 0.0011$  and  $0.017$  respectively; Figure 2a). No reduction in the proportion of slips was observed across the three exposures to the office paper surface ( $p = 0.19$ ) or between the second and third exposure to the wax paper surface ( $p = 0.15$ ). Required friction in the trials preceding the first three low-friction exposures did not vary with surface type, but did decrease from  $0.183 \pm 0.022$  to  $0.170 \pm 0.030$  between the first and second exposures ( $p = 0.0005$ ). It did not decrease again between the second and third exposures ( $0.171 \pm 0.027$ ;  $p = 0.85$ ).

When data from all low friction trials (n=620) were grouped according to a subject's prior knowledge level, the proportion of slips decreased with awareness for the

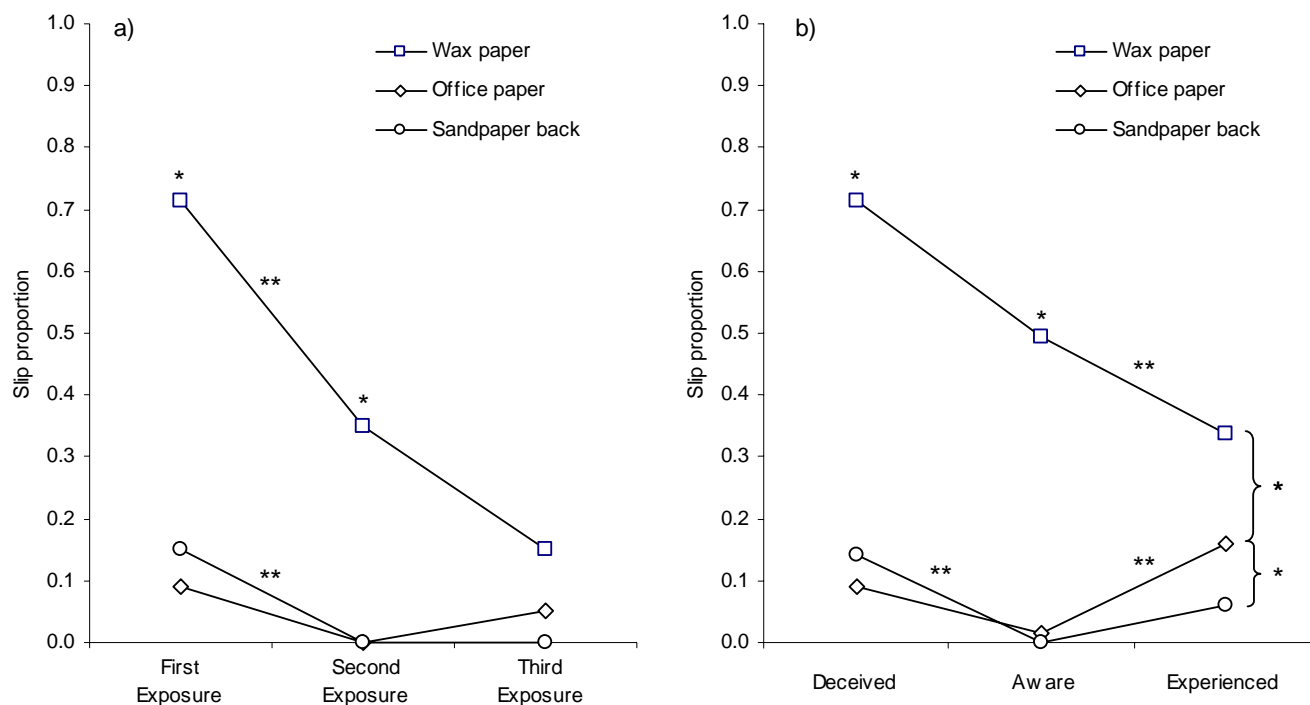


Figure 2. Proportion of low-friction trials generating a slip for a) the three surfaces (wax paper, office paper, sandpaper back) during the first three exposures, and b) the three levels of subject awareness (deceived, aware and experienced). Data from the first exposure and deceived condition are identical. The second and third exposures were under aware and possibly experienced conditions in Block 3. The aware and experienced conditions in b) consist of all slip trials from all blocks. \* designates significantly difference in proportion of slips between surface types; \*\* designates significant difference in proportion of slip between exposure or prior knowledge conditions.

Table 2. Number of trials (%) within a range of slip distances for deceived, aware and experienced groups.

Slip distance (mm)	Deceived	Aware	Experienced
-15 to 0	0 (0.0%)	6 (3.1%)	22 (6.1%)*
0 to 13	28 (43.8%)	119 (61.0%)*	220 (60.9%)*
13 to 27	16 (25.0%)	34 (17.4%)	51 (14.1%)*
27 to 50	4 (6.3%)	5 (2.6%)	15 (4.2%)
50 to 100	6 (9.4%)	6 (3.1%)*	12 (3.3%)*
100 to 200	0 (0.0%)	7 (3.6%)	13 (3.6%)
200 to 525	10 (15.6%)	18 (9.2%)	28 (7.8%)*
Total	64	195	361

\* Significantly different from deceived,  $p < 0.05$

sandpaper backing surface ( $p=0.003$ ), but not for the wax or office paper surfaces ( $p=0.074$  and  $0.093$  respectively) (Figure 2b). The addition of slip experience reduced the proportion of slips for the wax paper surface ( $p=0.035$ ). For all levels of prior knowledge, the proportion of slips was higher on the wax paper than on the other two surfaces ( $p<0.0012$ ). Slip distances diminished between the D and A conditions, but not between the A and E conditions (Table 2). The required friction decreased from  $0.183\pm 0.022$  for D trials to  $0.172\pm 0.029$  for A trials ( $p=0.008$ ) and decreased again to  $0.162\pm 0.024$  for E trials ( $p<0.001$ ). Data from the last three blocks of the 46 subjects who walked across all three low friction surfaces at slow, normal and fast walking speeds indicated that required friction did not vary with either walking speed or surface type.

Based on the logistic regression analyses, the probability of slipping was significantly related to both available and normalized friction ( $p<0.0001$ ). Despite being significant, the available friction regressions (Figures 3a,b, Table 3) were inferior to the normalized friction regressions (Figures 3c,d, Table 4) for a number of reasons. First, there were only three discrete levels of available friction with a relatively narrow range (0.10 to 0.19; Table 1), whereas a relatively wide range of required friction values (0.04 to 0.29) produced normalized friction values that were more continuously and broadly distributed (0.14 to 0.15). Second, the regression coefficients for the available friction regressions had standard errors 1.1 to 5.2 (average 2.6) times larger than the normalized friction regressions. And finally, the discrete nature of  $\mu_{available}$  yielded regressions that predicted no slips for any of the A or E trials despite a 19% slip rate in both data sets. For these reasons, the available friction regressions were not pursued further.

The normalized friction associated with a 50% probability of slipping was largest for the D trials and smallest for the E trials for both tribometers (Table 4, Figure 3c,d). Residual variations were not significantly different between either the D and A groups or

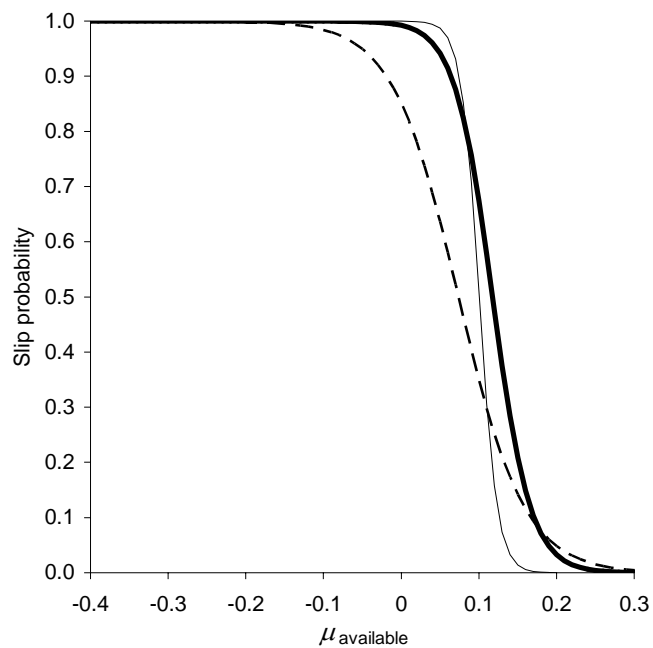
Table 3. Predicted value  $\pm$  standard error for the regression coefficients  $b_0$  and  $b_1$  as a function of available friction for the deceived, aware and experienced subjects using both tribometers. Also shown are the number of trials (N) and the available friction at 50% slip probability  $\mu_{avail-50}$ . 95<sup>th</sup> percentile confidence intervals shown in parentheses.

	N	$b_0$	$b_1$	$\mu_{avail-50}$
<b>Drag sled</b>				
Deceived	64	4.84 $\pm$ 1.42 (2.06 to 7.62)	-41.16 $\pm$ 10.57 (-61.87 to -20.44)	0.118 (0.093 to 0.134)
Aware	195	8.60 $\pm$ 2.11 (4.47 to 12.74)	-85.68 $\pm$ 20.30 (-125.46 to -45.90)	0.100 (0.093 to 0.108)
Experienced	361	1.74 $\pm$ 0.59 (0.59 to 2.90)	-23.62 $\pm$ 4.47 (-32.39 to -14.85)	0.074 (0.039 to 0.092)
<b>Variable incidence tribometer</b>				
Deceived	64	6.08 $\pm$ 1.68 (2.79 to 9.37)	-45.12 $\pm$ 11.22 (-67.11 to -23.12)	0.135 (0.112 to 0.149)
Aware	195	10.33 $\pm$ 2.47 (5.49 to 15.17)	-87.70 $\pm$ 20.38 (-127.65 to -47.76)	0.118 (0.109 to 0.123)
Experienced	361	2.32 $\pm$ 0.70 (0.96 to 3.69)	-25.04 $\pm$ 4.73 (-34.32 to -15.76)	0.093 (0.059 to 0.110)

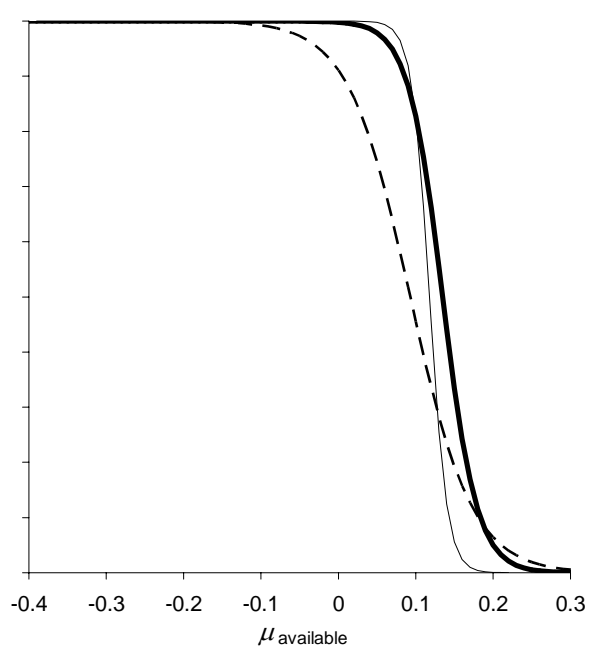
Table 4. Predicted value  $\pm$  standard error for the regression coefficients  $b_0$  and  $b_1$  as a function of normalized friction for the deceived, aware and experienced subjects using both tribometers. Also shown are the number of trials (N) and the friction difference at 50% slip probability  $(\mu_{avail} - \mu_{req})_{50}$ . 95<sup>th</sup> percentile confidence intervals shown in parentheses.

	N	$b_0$	$b_1$	$(\mu_{avail} - \mu_{req})_{50}$
<b>Drag sled</b>				
Deceived	64	-2.41 $\pm$ 0.61 (-3.61 to -1.20)	-34.4 $\pm$ 9.9 (-53.8 to -15.0)	-0.070 (-0.103 to -0.052)
Aware	195	-4.11 $\pm$ 0.60 (-5.28 to -2.93)	-48.7 $\pm$ 8.2 (-64.8 to -32.6)	-0.084 (-0.098 to -0.074)
Experienced	361	-2.16 $\pm$ 0.21 (-2.58 to -1.75)	-23.1 $\pm$ 3.8 (-30.6 to -15.5)	-0.094 (-0.124 to -0.077)
Combined	620	-2.46 $\pm$ 0.19 (-2.82 to -2.09)	-30.57 $\pm$ 3.21 (-36.87 to -24.27)	-0.080 (-0.092 to -0.071)
<b>Variable incidence tribometer</b>				
Deceived	64	-1.95 $\pm$ 0.50 (-2.94 to -0.97)	-36.6 $\pm$ 10.5 (-57.1 to -16.0)	-0.053 (-0.085 to -0.037)
Aware	195	-3.32 $\pm$ 0.47 (-4.24 to -2.39)	-49.1 $\pm$ 8.2 (-65.2 to 33.0)	-0.068 (-0.082 to -0.058)
Experienced	361	-1.82 $\pm$ 0.17 (-2.16 to -1.48)	-23.9 $\pm$ 4.0 (-31.7 to -16.0)	-0.076 (-0.105 to -0.060)
Combined	620	-2.10 $\pm$ 0.16 (-2.41 to -1.80)	-30.64 $\pm$ 3.26 (-37.04 to -24.25)	-0.069 (-0.081 to -0.060)

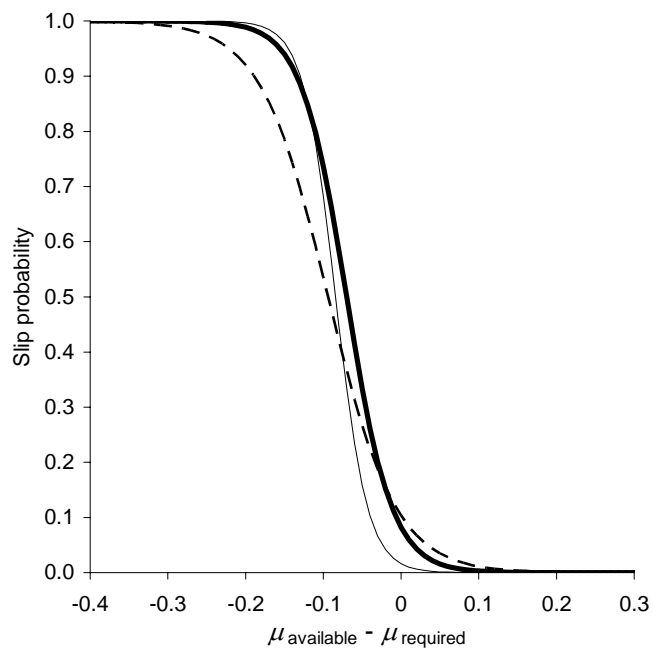
a) Drag sled



b) Variable incidence tribometer



c) Drag sled



d) Variable incidence tribometer

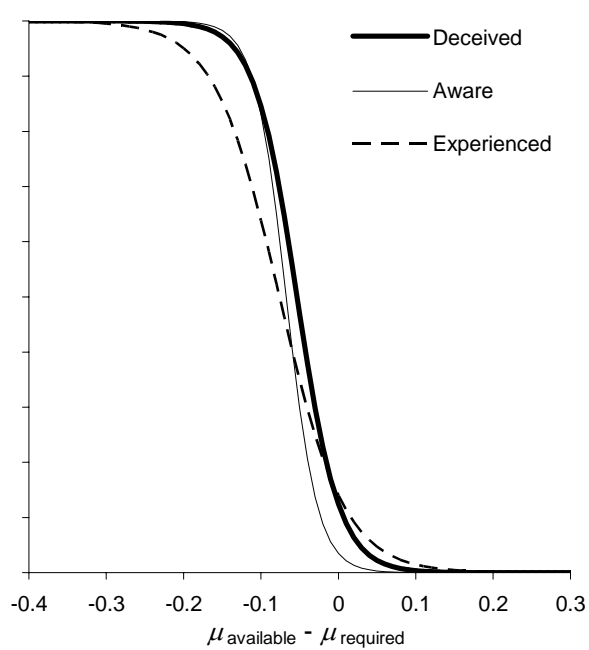


Figure 3. Probability of slipping as a function of available friction (a,b) and normalized friction (c,d) for the drag sled (a,c) and variable incidence tribometer (English XL) (b,d) using the deceived, aware and experienced data sets.

the D and E groups, and thus Wald statistics were used to compare the regression coefficients. These comparisons showed that  $b_0$  was significantly lower in the A group than in the D group for both tribometers ( $p=0.048$  for both). No other differences in  $b_0$  or  $b_1$  were found between the D and A groups or the D and E groups ( $p>0.25$ ). The residual variation in the A group was 53% smaller than in the E group ( $p=0.002$ ) and thus Wald statistics could not be used to directly compare the regression coefficients. A likelihood ratio test however showed that neither of the coefficients ( $b_0$  or  $b_1$ ) were significantly different between the A and E groups ( $p=0.96$ ).

### **Discussion**

The current study demonstrates a decrease in the probability of slipping with both repeated exposure and changes in a subject's prior knowledge of the slip conditions. Required friction and slip distance also changed after the first low friction exposure, suggesting that subjects altered their normal gait to reduce both the probability of slipping and the severity of a slip if it occurs. Previous studies have observed a variety of changes in lower limb muscle activity and the kinematics and kinetics of normal gait with both awareness of a potential slip and prior slip experience (Cham and Redfern, 2001; You et al., 2001; Marigold and Patla, 2002; Heiden et al., in review). Large adaptations to slip recovery responses with repeated exposures have also been reported by Marigold and Patla (2003). Thus the presence of adaptations in the current data set indicate its suitability for the primary goal of this study: to quantify how the relationship between slip probability and shoe/floor friction is affected by the awareness and prior slip experience of human subjects.

The regression models using available friction could not respond to the observed adaptations in required friction whereas the models using normalized could. Using available friction, the 50% slip-probability ( $\mu_{available-50}$ ) diminished by 0.044 (DS) and 0.042

(VIT) between the deceived and experienced trials (Table 3). Using normalized friction, these values decreased by only 0.024 (DS) and 0.023 (VIT) between the deceived and experienced trials (Table 4). The smaller reduction suggests normalization removed about half of the bias introduced by awareness and prior slip experience. Normalizing friction also has the potential to account for inter-subject and inter-task variations in required friction. The smaller standard errors associated with the regression coefficients from the normalized friction regressions show the benefit of accounting for inter-subject variations. The ability of friction normalization to account for inter-task variations in required friction cannot be evaluated with the current data, but if demonstrated, would allow the same normalized regression curves to be applied to multiple activities like walking running, turning or pushing. Further work is needed to demonstrate this potential versatility of normalizing friction.

If the deceived subjects' data represent the probability of unexpected slips in the general population, then awareness of a potentially slippery surface shifts the slip probability curve to the left (significant decrease in  $b_0$ ), but does not change its shape/slope (no change in  $b_1$ ) (Figures 3c,d). The subsequent addition of slip experience appears to eliminate this leftward shift. Despite tighter confidence intervals, the regression coefficients for the experienced trials were not significantly different from those of the deceived trials. The reduction in slip rate, slip distance and required friction between the deceived and aware groups is consistent with a lower probability of slipping in aware subjects; however, it is not clear why subsequently acquiring experience – which further lowers the required friction, though not the slip rate or distance – eliminates the difference between deceived and experienced groups. It is possible that awareness of a potential slip without prior slip experience creates anxiety that diminishes after subject gain slip experience. This hypothesis may also explain the different muscle, kinematic and kinetic

adaptations to normal gait observed in aware versus experienced subjects (Heiden et al., in review).

From a practical perspective, the similarity between the slip probability models for deceived and experienced subjects is a boon for the tribometer validation process. Based on the current findings, a tribometer's ability to predict slips can be determined using data from both deceived and experienced subjects – even though experienced subjects adapt their normal gait. Additional work are needed to determine if the findings observed here using three paper surfaces and two tribometers extend to other tribometers and other surfaces – particularly contaminated surfaces responsible for many slips and falls (Manning, 1988). If so, validation data could be generated using a small pool of subjects exposed to many slips rather than a large pool of deceived subjects exposed to a single slip. Optimally, validation studies could include a deception trial prior to multiple experienced trials to allow confirmation of the similarity between deceived and experienced responses for the specific protocol being used.

Brady et al. (2000) reported a 50% chance of falling for a slip distance of 318mm, but none of the 37 trials with slip distances greater than 318mm in the current study led to a fall. Although protocol differences may explain this difference (they used bare feet on mineral-oil coated vinyl), the absence of falls in the current study highlight an important limitation of our study: its conclusions apply to the probability of slipping, not falling. Pronounced adaptations to falling (Marigold and Patla, 2003) suggest that experienced subjects will not yield data suitable for validating a tribometer's ability to predict combined slips and falls.

Differences between the regression coefficients for the deceived and aware data were isolated to the intercept ( $b_0$ ). Since changes in  $b_0$  only slide the regression curve horizontally left or right, the aware data can be corrected by increasing its normalized

friction by the difference between the  $(\mu_{available} - \mu_{required})_{50}$  values for the deceived and aware data. This difference was 0.142 and 0.141 for the DS and VIT respectively (Table 4). With this correction, data from all three groups can be pooled and an overall regression computed ("combined" values in Table 4, Figure 4). Based on the combined data, the normalized friction associated with a 50% probability of slipping is between -0.092 and -0.071 for the DS and between -0.081 and -0.060 for the VIT. This narrow range (0.021 for both tribometers) suggests that tribometers can accurately predict the slip risk of a population over all but a small range of normalized friction values. In practice, however, the available friction may need to be normalized by the average required friction of a population rather than the required friction of a specific individual, and this will increase the size of the confidence interval associated with a 50% slip probability. In addition, the

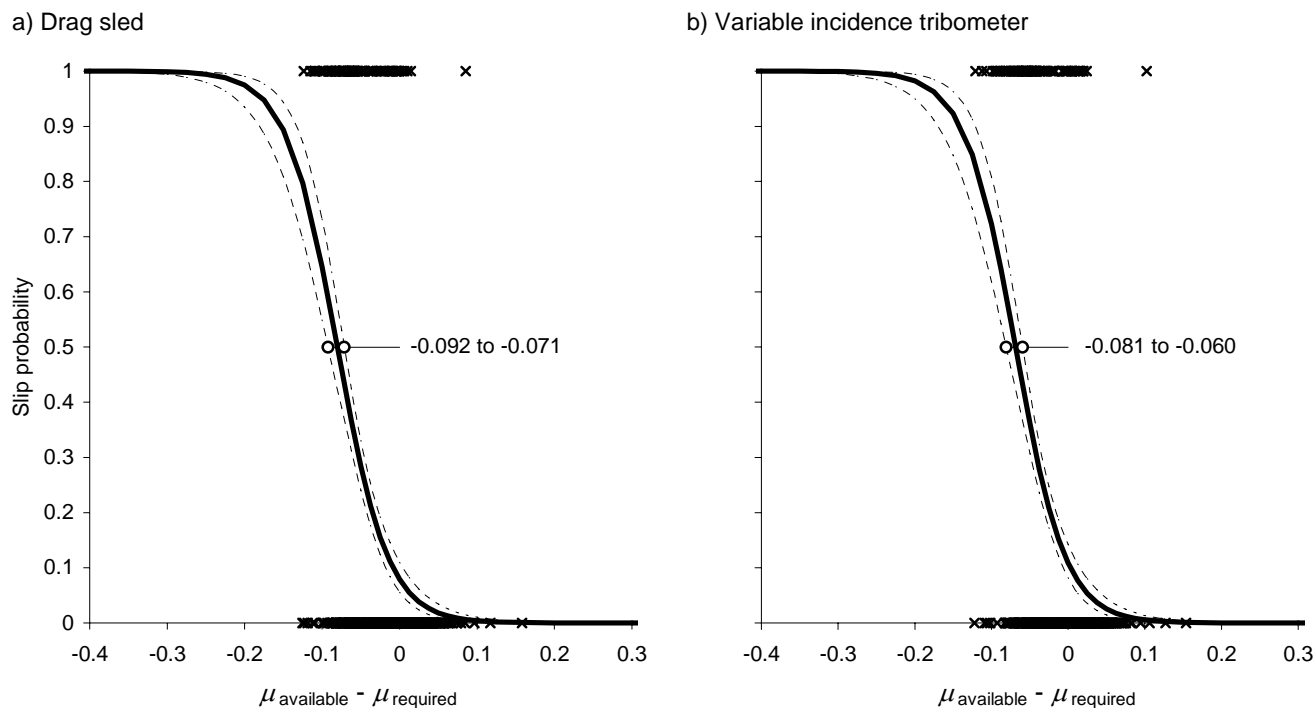


Figure 4. Probability of slipping as a function of available friction for two tribometers: a, the drag sled; and b, the variable incidence tribometer (English XL) using the combined adjusted data sets. The  $\times$  symbols depict the actual data and the dashed lines depict the 95<sup>th</sup> percentile confidence intervals for the regression (thick solid line). Shown also are the 95<sup>th</sup> %ile confidence ranges for the 50% slip probability (hollow circles).

confidence bands in Figure 4 depict the range in which 95% of the best-fit regressions will lie, whereas estimates of an individual's slip risk for a specific measured friction will be larger.

The large difference in slip probability (70% versus 15%) between wax paper and office paper (a 0.05 friction difference) indicates that tribometers must resolve small differences in friction to effectively distinguish surface slipperiness and accurately predict slip probability in the transition region. Both tribometers tested here differentiated between these two surfaces, but this may not occur under all operating conditions. In practice, four tribometer measurements are often averaged to estimate the friction of a surface (ASTM, 1996; English, 2003). Monte Carlo simulations using the wax and office paper friction distributions (Table 1) to generate four measurements per surface indicated that the DS and VIT would statistically differentiate (t-test,  $p < 0.05$ ) these two surfaces 63% and 90% of the time respectively. Eight measurements improved these values to 93% and 99.9% respectively. Based on these simulations, eight or more tribometer measurements should be considered for field measurements using tribometers.

The current study is based on the assumption that our deceived slips are similar to unexpected slips that occur in the general population. The validity of this assumption is difficult to test. The fact that we observed differences between the deceived and other groups suggests that we were at least partially successful in reproducing actual unexpected slips. The results of this study are also limited by use of only two tribometers, both of which measured similar though not identical friction values for all three materials. This uniformity may not be typical of all or even these tribometers, particularly under conditions involving contaminants (Chang and Matz 2001; Marpet 1996; Marpet and Fleischer 1997; Powers et al 1999). A benefit of the current protocol, however, is that

other tribometers can subsequently measure the friction of the same paper surfaces and then re-use the current data to generate slip probability curves.

The paper slip surfaces used in the current study are different from the fluid contaminants (Cham and Redfern, 2002; Andres et al., 1992; You et al., 2001; Brady et al., 2000; Bunternngchit et al., 2000; Hanson et al., 1999; Lockhart et al., 2003), rollers (Marigold and Patla, 2002; Marigold et al., 2003; Oates et al., 2004) and sliding platforms (Pai et al., 2003; Pavol et al., 2004) used by other researchers. Paper was chosen to eliminate or minimize potential problems with each of these other systems. The sliding friction (drag) of fluid contaminants is sensitive to film thickness (Streeter and Wylie, 1981), which varies with shoe width, shoe angle, sole material, tread pattern and slip speed – all of which may vary between subjects and some of which may vary between slips by the same subject. Rollers eliminate many of these problems, but introduce others: the heel can land between the rollers and each of the rollers generates an inertial reaction force as it is accelerated to the slip speed of the shoe. Sliding platforms have a larger mass than rollers and thus have a large inertial reaction force that is also slip acceleration dependent. With paper surfaces, the coefficient of friction is reproducible between tests and the surface is continuous and flat. The individual surfaces have a very low mass (8 to 18% of the shoe mass) and therefore inertial reaction forces are minimized. Although slips on paper account for only a small percentage of actual slip and fall injuries, it provided a reproducible and realistic slip environment which met the needs of this study.

In summary, the results of the current study show that gait adaptations due to subject awareness bias the slip risk curve toward underestimating the actual risk of slipping, whereas the additional adaptations that occur once slip experience has been acquired eliminate this bias. Thus data from subjects with prior slip experience can be used to determine the slip risk, but not fall risk, of unprepared subjects.

### **Implications for Future Research on Occupational Health**

This work provides a basis for using human subject data to generate slip risk curves for different tribometers. The results of the current study suggest that data acquired from subjects who have slipped multiple times do not need to be corrected to be used to generate slip risk curves for a tribometer. This greatly simplifies the tribometer validation process and can now be applied to other tribometers. Once validated, a tribometer can be used to predict the risk of slipping for various floor surfaces.

Despite these positive findings, a number of significant research questions remain. For instance, this work does not address the risk of falling – the cause of many slip-related injuries. Since slips precede falls, eliminating slips will also eliminate falls. This work is also limited to walking. The applicability of these findings to other tasks such as running, turning, pushing or other work-related tasks requires further work.

### **Policy and Prevention**

#### ***a) Identification of policy and prevention implications arising from the research***

The results of this study provide a foundation upon which to conduct further research that could lead to specific policy and prevention implications. Depending on the results of future work, it is foreseeable that specific tribometers and minimum floor friction levels may be stipulated in future WCB policies.

#### ***b) An identification of relevant user groups for the research results***

The relevant audience for the current study is academic researchers, safety engineers and officers, and the footwear/flooring industries.

#### ***c) A description of any policy-related interactions undertaken by the Applicant***

None.

### **Dissemination/Knowledge Transfer**

The research conducted for the grant has yielded three manuscripts (see below), the latter of which addresses the primary objectives of this study.

Heiden TL, Sanderson DJ, Inglis JT, Siegmund GP. Adaptations to normal human gait on potentially slippery surfaces: the effects of awareness and prior slip experience. Submitted to Gait and Posture, January 21, 2005; resubmitted with revisions May 16, 2005.

Heiden TL, Sanderson DJ, Inglis JT, Siegmund GP. Interlimb transfer of gait adaptations following a slip. Submitted to Experimental Brain Research May 9, 2005.

Siegmund GP, Heiden TL, Sanderson DJ, Inglis JT, Brault JR. The effect of subject awareness and prior experience on tribometer-based predictions of slip probability. Submitted May 16, 2005.

In addition to these three manuscripts, three abstracts for conferences have been either presented or submitted:

Heiden TL, Sanderson DJ, Inglis JT, Siegmund GP (2004). Experience, rather than knowledge, of a slip induces gait adjustments. 34<sup>th</sup> Annual Meeting. Society for Neuroscience, Abstract 415.10, San Diego, CA, October 23-28, 2004.

Siegmund GP, Heiden TL, Sanderson DJ, Inglis JT. Interlimb transfer of gait adaptations following a slip. To be presented to 35<sup>th</sup> Annual Meeting. Society for Neuroscience, Washington, DC, November 12-16, 2005.

Siegmund GP, Heiden TL, Sanderson DJ, Inglis JT, Brault JR. Subject awareness and prior slip experience affect different aspects of normal human gait. To be presented to 19<sup>th</sup> Annual International Occupational Ergonomics and Safety Conference, Las Vegas, June 27-29, 2005.

An additional manuscript examining the detailed heel slip kinematics may be published if subsequent analyses generate additional insights.

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