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Predicting slips based on the STM 603 whole-footwear tribometer under different coefficient of friction testing conditions

Kurt E. Beschorner[1,*], **Arian Iraqi**[2], **Mark S. Redfern**[3], **Rakié Cham**[4,5], **Yue Li**[6]

[1]Department of Bioengineering, University of Pittsburgh, Benedum Hall 302, 3700 O'Hara St., Pittsburgh, PA 15261,

[2]Department of Bioengineering, University of Pittsburgh, Benedum Hall 302, 3700 O'Hara St., Pittsburgh, PA 15261,

[3]Department of Bioengineering, University of Pittsburgh, Benedum Hall 302, 3700 O'Hara St., Pittsburgh, PA 15261,

[4]Department of Bioengineering, University of Pittsburgh, Benedum Hall 302, 3700 O'Hara St., Pittsburgh, PA 15261,

[5]Department of Physical Therapy, University of Pittsburgh

[6]Toronto Rehabilitation Institute, University Health Network, 550 University Avenue,

Abstract

Assessing footwear slip-resistance is critical to preventing slip and fall accidents. The STM603 (SATRA Technology) is commonly used to assess footwear friction but its ability to predict human slips while walking is unclear. This study assessed this apparatus' ability to predict slips across footwear designs and to determine if modifying the test parameters alters predictions. The available coefficient of friction (ACOF) was measured with the device for nine different footwear designs using twelve testing conditions with varying vertical force, speed and shoe angle. The occurrence of slipping and required coefficient of friction was quantified from human gait data including 124 exposures to liquid contaminants. ACOF values varied across the test conditions leading to different slip prediction models. Generally, a larger shoe angle (13°) and higher vertical forces (400 or 500 N) modestly improved predictions of slipping. This study can potentially guide improvements in predictive test conditions for this device.

Practitioner Summary:

Frictional measures by the STM603 (SATRA Technology) were able to predict human slips under liquid contaminant conditions. Test parameters did have an influence on the measurements. An increased shoe-floor testing angle resulted in better slip predictions than test methods specified in the ASTM F2913 standard.

[*]Corresponding author: +1(412)624-7577, beschorn@pitt.edu.

Keywords

Coefficient of friction; required coefficient of friction; slip-resistance; slips, trips and falls; footwear testing

Introduction:

Falling accidents are a major occupational and public health problem. In the United States, falls are the leading cause of injuries that result in an emergency room visit (Centers for Disease Control 2012). Falls during 2014 in the United States are estimated to have an associated lifetime cost of $169 billion (Florence *et al.* 2015). Falls represent 27% of nonfatal occupational injuries in the United States (U.S. Department of Labor- Bureau of Labor Statistics 2016) and 29% of nonfatal occupational injuries in Great Britain (Spence 2017). Falls in the United States cost approximately $18 billion in worker's compensation claims (Liberty Mutual Research Institute for Safety 2017). The incidence of occupational falls are increasing while other types of injuries are decreasing (Chang *et al.* 2016). Slipping is the source of between 40 and 50% of occupational falling injuries (Courtney *et al.* 2001) and causes approximately 25% of falls among community-dwelling older adults (Berg *et al.* 1997). Clearly, prevention of slip and fall accidents could lead to positive occupational and public health outcomes.

The occurrence of a slipping event can be predicted based on the friction requirements of walking and the available friction between the footwear and floor surface. A slip becomes less likely as the difference between the available coefficient of friction (ACOF) and the required coefficient of friction (RCOF) increase (Hanson *et al.* 1999, Burnfield and Powers 2006, Siegmund *et al.* 2006, Tsai and Powers 2008). RCOF is calculated from the normal and friction (vertical and horizontal, respectively, during level walking) ground reaction forces during unperturbed gait that are typically measured with a force plate (Chang *et al.* 2011, Beschorner *et al.* 2016). ACOF is typically measured by sliding the footwear outsole or a sample of footwear material against a floor surface and measuring the friction and normal forces (Grönqvist 1995, Chang *et al.* 2001a, Gronqvist *et al.* 2003, Siegmund *et al.* 2006, Beschorner *et al.* 2007, Beschorner and Singh 2012, Blanchette and Powers 2015b, Blanchette and Powers 2015a). Logistic regression curves have been used to predict slip risk based on the independent variables: the difference between ACOF and RCOF (Hanson *et al.* 1999, Burnfield and Powers 2006, Siegmund *et al.* 2006, Tsai and Powers 2008); ACOF (Burnfield and Powers 2006, Siegmund *et al.* 2006); and RCOF (Beschorner *et al.* 2016). Furthermore, these curves can be used to assess the validity, sensitivity, or bias of ACOF and RCOF measures to predict slips (Blanchette and Powers 2015b, Beschorner *et al.* 2016, Iraqi *et al.* 2018a).

One common device used for ACOF testing in laboratory settings is the STM 603 (SATRA Technology) (Wilson 1990, Wilson 1996, Blanchette and Powers 2015b, Blanchette and Powers 2015a, Allen 2016, Morio *et al.* 2017). This device is capable of performing ASTM and ISO testing standards (ASTM 2011, International Standards Organization 2012). Furthermore, the STM 603 device is listed as the sole source that is known to be able to perform the ASTM F2913 testing standard (2011). The STM 603 device was among the first commercially-available devices to test an entire sample of footwear and has the ability to alter the shoe-floor angle, vertical force and speed during testing to better match the actual conditions under which walking and potential slips occur. The STM 603 device uses an entire footwear specimen, against a flooring surface. The footwear is set at a fixed angle to the floor to represent the angle occurring shortly after heel contact and a vertical force is applied. The floor is then moved relative to the footwear at a given speed and the vertical and horizontal forces are recorded. The ACOF is calculated as the ratio of the horizontal to vertical forces occurring at 0.10 ± 0.01 s after the initiation of sliding. Chang, et al. suggest that whole-footwear testing devices are better at reproducing the tribological interaction between footwear and flooring compared to current portable devices (2016). The STM 603 is a good candidate for footwear-floor traction testing based on the devices wide usage, compatibility with standards, and ability to test entire footwear specimens.

While the STM 603 is widely used to measure slip resistance, few studies have examined the validity of this device in predicting actual slips while walking. One study that was performed found that the difference between ACOF measured by the device and RCOF during gait predicted slipping (Blanchette and Powers 2015b). The study used only one shoe-floor-contaminant condition, therefore the observed effects are attributed to changes in RCOF across individuals as opposed to differences in ACOF across footwear-floor-contaminant conditions. Reports generated by the Health and Safety Laboratory (UK) have performed correlation analyses between ACOF values collected using the STM 603 device under different testing conditions and a human-based ramp test method (Hunwin *et al.* 2010, Darby 2012). One of their two studies showed that the correlation between these two test methods could be improved by reducing the normal force and increasing the sliding speed (Hunwin *et al.* 2010) whereas the other study showed that good agreement could not be reached under any of the testing conditions that were considered (Darby 2012). However, the ramp test is performed using trained subjects that take small forward and backward steps on an inclined surface, which likely does not resemble the foot dynamics that occur during actual unexpected slip events (Deutsches Institut für Normeng 2003). Thus, an important gap exists in the literature regarding the ability of the device to predict unexpected slips across different footwear and contaminant conditions.

Testing parameters used when measuring ACOF impact the results. Previous research has identified complex interaction effects between normal force, sliding speed and shoe-floor angle for various devices (Redfern and Bidanda 1994, Beschorner *et al.* 2007, Blanchette and Powers 2015b). Various standards or guidelines dictate different testing conditions. For the STM 603 device, the typical parameters include a normal force of 400 N (for footwear sizes under European 40) or 500 N (for footwear sizes European 40 and above); sliding speed of 0.3 m/s; and a shoe-floor angle of 7° (ASTM 2011, International Standards Organization 2012). Our previous research has raised questions whether these testing conditions reflect the under-heel conditions during slipping. For example, studies on unexpected slips have determined that the shoe angle is between 15 and 24° at the moment that the foot starts to slip, which is greater than the 7° used in these testing methods (Albert *et al.* 2017, Iraqi *et al.* 2018b). Furthermore, the normal forces at slip initiation are typically less than 300 N but then achieve approximately 500 N during the peak slipping speed (Iraqi *et al.* 2018b). While these previous studies indicate deviations between testing conditions and slipping biomechanics at slip-start, it should be noted that the under-heel conditions vary over time and that lower shoe angles (Albert *et al.* 2017) and higher normal forces (Iraqi *et al.* 2018b) are observed at peak sliding speed, similar to those commonly used by the STM 603 device. Thus, it could be argued that a range of conditions could be reasonably considered for ACOF testing.

Choice of testing parameters for slip testing devices should approximate the dynamics of slipping during friction testing to capture the relevant tribological mechanisms explaining slip and fall events (Chang *et al.* 2016). However, few studies have been conducted to quantify differences in predicting slips across different friction measurement methods that are within the range of conditions relevant to human slipping. Blanchette and Powers examined how using different testing conditions with the STM 603 predicted unexpected slips (Blanchette and Powers 2015b). However, as mentioned previously, this study only considered a single footwear-floor-contaminant condition. Therefore, further investigation on this topic is warranted.

The purpose of this study was to quantify the predictive ability of the ACOF measured with the STM 603 device and RCOF values measured from gait to predict slip events in humans. In addition, predictive models were developed under different ACOF testing conditions to determine the influence of these testing conditions on the quality of predictions.

Methods:

Human gait captured in a motion capture lab and ACOF data collected from the STM 603 device were used to develop slip-prediction models. The walking studies included 89 subjects (age of 22.6 ± 3.7 years; body height of 174.4 ± 7.9 cm; body mass of 71.8 ± 15.1 kg; 35 female) exposed to liquid contaminants for a total of 159 exposures, while wearing one of the nine different footwear designs. Of these 89 subjects, 19 were exposed to a liquid contaminant one time and the other 70 were exposed to a liquid contaminant two times. Four exposures were excluded because the subject reported seeing the contaminant prior to stepping on it and 5 subjects were excluded because they did not step completely on the contaminated flooring during the exposure trial. As described later in the data analysis section, data from the second exposure to a liquid contaminant was excluded if the subject slipped during their first exposure. The number of exposures per footwear design that were included ranged from 8 to 19 (Table 1). The selected footwear included 6 low-height shoes and 3 ankle-high boots (Figure 1, Supplementary Table 1). The tread on two of the shoes (S1 and S3) was mechanically abraded prior to testing. The shoe, S1, was slightly abraded using abrasive paper in order to remove the outer-most layer of the shoe material. The shoe, S3, had the tread features completely removed using abrasive paper with particles that were approximately 180 μm in size (i.e., “80 grit sandpaper”). The contaminants included diluted glycerol (ratios by volume: 50% glycerol/50% water; 75% glycerol/25% water; and 90% glycerol/10% water) and canola oil (Table 1). The same manufacturer and model of vinyl composite tile (Armstrong Earthstone ®) was used for all experiments. Human gait data were pooled from different studies within our laboratory that all used similar procedures (Beschorner and Cham 2008, Beschorner *et al.* 2013, Beschorner *et al.* 2014, Beschorner *et* *al.* 2016, Jones *et al.* 2017, Iraqi *et al.* 2018a). Procedural differences across these studies include: 1) only a single footwear design was worn by each subject in one study (Beschorner and Cham, 2008) whereas multiple designs were worn in the other studies and 2) three baseline trials were collected in one study (Beschorner and Cham, 2008) whereas five baseline trials were collected in the other studies before the first exposure to a contaminant. All of these studies were approved by the University of Pittsburgh Institutional Review Board. Subjects were aware that they might step on a slippery surface but were unaware of when, where, or the method of making the surface slippery. Subjects walked at a comfortable, self-selected pace and completed between 3 and 20 practice trials before being exposed to a contaminant. Ground reaction forces during 3–5 unperturbed gait trials on a dry surface preceding the exposure to a contaminant were used to quantify RCOF. The occurrence of a slip was determined from heel kinematic data using a slip distance threshold of 3 cm (Leamon and Li 1990, Beschorner *et al.* 2016, Albert *et al.* 2017, Iraqi *et al.* 2018a).

ACOF Data Collection

ACOF was measured across 12 different testing conditions, which included a factorial design using three force levels (250 N, 400 N, and 500 N), two sliding speeds (0.3 m/s and 0.5 m/s) and two angles (7° and 13°). The force levels of 400 N and 500 N; the sliding speed of 0.3 m/s and the angle of 7° were selected because of their use in the ASTM F2913 standard. The lower force of 250 N was considered based on recent research demonstrating that a lower force may have better relevance to slipping (Iraqi *et al.* 2018a, Iraqi *et al.* 2018b). The sliding speed of 0.5 m/s was selected based on the fact that the shoe or boot typically achieves higher sliding speeds before and after slip initiation (Redfern *et al.* 2001, Beschorner and Cham 2008, Albert *et al.* 2017) and this is the highest achievable speed by the device. The shoe-floor angle of 13° was selected because shoe-floor angles of 15 to 24° have been observed at slip-initiation (Albert *et al.* 2017, Iraqi *et al.* 2018b) and this was the highest angle achievable by the device. New test program files were created for all of the force and speed conditions besides those used in the F2913 condition (500 N, 0.3 m/s) by matching the other parameters (snapshot window of +/− 10 ms, time that the footwear was held statically before the flooring started to slide = 200 ms, etc.) to those occurring in the F2913 condition. The test conditions for the F2913 standard for sizes greater than size 40 were preloaded by the propriety software (slipMASTER v. 3.2.0.1., SATRA Technology, Kettering, UK). The ASTM F2913 test file (for footwear greater than size 40) was used when all of the testing conditions (force, speed and shoe-floor angle) matched the ASTM standard. One slight deviation was made relative to the standard related to shoe-floor angle. The standard specifies that a wedge be used to set the angle beneath the heel. In preliminary testing, it was determined that this was not a repeatable or reliable method for footwear with a rounded heel since the angle of the heel varies across its surface. Therefore, the angle of the frame holding the footwear relative to the floor surface was set to the desired shoe angle. For flat-bottomed footwear, this method yielded the same angle as the wedge method. A shoe size of 42 (European scale) was used for all experiments and the largest size last (available in each size) that could fit the footwear specimen was used.

The order of test conditions within each footwear design was randomized. The shoes with canola oil contaminant were tested last due to concerns that the oil could change the surface of the VCT floor surface. A total of five tests were averaged for each condition. The heel surface was pre-wetted with the contaminant prior to testing to ensure that the first trial where the heel was dry would not vary relative to the other trials. The contaminant was spread across the VCT between each trial to ensure full coverage consistent with the gait trials where subjects were exposed to the contaminant. If the ACOF varied more than 0.01 between the first and last trial, then an additional trial was collected and the first trial was omitted. The floor surface was cleaned with room-temperature water and dried with a low-lint towel when the contaminant was changed. ACOF values were taken directly from the software.

Human Testing Procedures:

All of the human walking studies from which data were used in this analysis were performed by the same research group under similar protocols (Beschorner and Cham 2008, Beschorner *et al.* 2013, Beschorner *et al.* 2014, Beschorner *et al.* 2016, Jones *et al.* 2017, Iraqi *et al.* 2018a). Briefly, subjects donned a safety harness for fall protection and wore 79 reflective markers. Heel kinematics were assessed based on a marker placed at the most posterior point of the heel approximately 20 mm above the ground (inferior heel). This marker was removed in certain cases to prevent it from colliding with the floor surface during swing phase. In these cases, the marker was virtually replaced using a rigid body assumption based on other markers that were placed on the rear-foot. One marker was placed on the posterior section of the heel about 50 mm superior to the inferior heel marker while the other two markers were placed on the medial and lateral parts of the heel about 100 mm anterior from the inferior heel. The marker positions were recorded using motion capture cameras (Vicon M2 for shoe S1 and Vicon T40s system for all other types of footwear, Oxford, UK) with a sampling frequency of 120 Hz. Participants were directed to ambulate across a walkway. Prior to each gait trial, participants were asked to face away from the walkway, work on a word puzzle and/or listen to music using headphones for a minute. The lights were dimmed during the entire experiments to limit visual cues from the liquid contaminant that was applied on the floor surface. Participants' starting point was adjusted until 3–5 trials were collected where their left foot and only their left foot hit within the boundaries of the force plate (4060A, BERTEC Corporation, Columbus, OH, USA). Then the participants were unexpectedly exposed to a gait trial with a liquid contaminant applied to the flooring on the force plate. Participants were given a different pair of footwear and repeated 15–20 gait trials on a dry surface in order to reduce anticipation of a slip. (Chambers *et al.* 2014) These trials were followed by a second unexpected exposure to the liquid contaminant. Ground reaction forces were sampled at 1080 Hz and time-synchronized with the position data. The force plate included a built-in anti-aliasing filter with a cutoff frequency of 500 Hz.

Data analysis:

The ground reaction forces and foot motion were used to quantify RCOF and slip distance, respectively. The RCOF was quantified from the ground reaction forces based on a method utilized by Chang et al. (Chang *et al.* 2011, Beschorner *et al.* 2016). RCOF was the peak ratio of resultant friction force to normal force when all of the following criteria were met: a vertical force of above 100 N; a force in the anterior direction applied to the floor by the footwear; a local maximum in the resultant friction force; and within 200 ms of heel contact (Figure 2A). The ground reaction forces were filtered prior to calculating the ratio of friction to normal forces using a fourth-order low-pass Butterworth filter with zero-lag and a cutoff frequency of 36 Hz (Chang *et al.* 2011). The slip distance was defined as the resultant displacement between slip initiation and the end of the slip (Figure 2B). The time of slip initiation was defined as the first local minimum in sliding speed after heel strike (Strandberg and Lanshammar 1981, Lockhart *et al.* 2003, Beschorner *et al.* 2016, Albert *et al.* 2017) (Figure 2B), where heel strike was defined as the time point where the vertical force first exceeded 25 N (Iraqi *et al.* 2018a, Iraqi *et al.* 2018b). The time of the end of the slip was defined as the first local minimum in sliding speed after peak sliding speed (Figure 2B). The peak sliding speed was defined as the first local maximum in sliding speed at least 50 ms after heel strike (Moyer 2006). For these calculations, heel speed was calculated as the resultant speed using a 2-point differentiation method. A phaseless 4th order low-pass Butterworth filter with a cutoff frequency of 24 Hz was used to filter position data prior to calculating speed. A trial was categorized as a slip if the slip distance exceeded 3 cm and was categorized as a non-slip if the slip distance was less than 3 cm (Leamon and Li 1990, Beschorner *et al.* 2016, Albert *et al.* 2017, Iraqi *et al.* 2018a).

Precautions were taken to minimize the potential influence of subjects' anticipating a slippery condition while walking. Data from a second exposure to a slippery condition were excluded if a slip occurred during the first exposure (n = 23). This exclusion was based on research showing that subjects alter gait if they have experienced a slip previously (Andres *et al.* 1992, Marigold and Patla 2002, Heiden *et al.* 2006, Beringer *et al.* 2014). Also, the second exposure was excluded if a reduction in RCOF of more than 16% was observed (n = 3). This threshold of 16% is based on previous research on gait changes when slippery surfaces are being anticipated (Cham and Redfern 2002a).

Logistic regression models were developed using ACOF-RCOF as the predictor and the slip outcome (slip or non-slip) as the dependent variable. Specifically, one model with *ACOF-RCOF* (Eq. 1), the difference between ACOF and RCOF, as the predictor was generated for each set of testing conditions, resulting in twelve different models.

$$\text{Slip\_}Probability(\%) = \frac{100}{1 + e^{\beta_0 + \beta_1 * (ACOF - RCOF)}} \qquad \text{Eq. 1}$$

Slip_Probability(%) is the predicted probability of a slip presented as a percent. Two coefficients, β_0 and β_1, are fit to optimally match the model to the data. Individual RCOF values were used for each participant as opposed to grouped means consistent with recommendations by Chang et al. (2016). A Bonferroni correction was used to correct for multiple comparisons (α = 0.05/12 = 0.004). The area under the curve (AUC) measure from receiver operating characteristic (ROC) curves were used to assess the quality of the ACOF-RCOF prediction models. AUC values closer to 1 indicate a better quality model and values closer to 0.5 indicate a poorer quality model. The AUC from the 12 models were compared using a χ^2 test for equivalence. If this test revealed a difference across the models, post-hoc χ^2 tests were performed. Given the high number of pairwise comparisons, post-hoc tests with Bonferroni correction (α = 0.05/11 = 0.005) were only performed for comparisons between the test condition used in ASTM F2913 and the 11 other testing conditions. This allowed us to identify the test conditions that led to significantly better or worse predictions than the current standard method. The point on the ROC curve that deviated the most from a line with a slope of 1 was identified as the point that best balanced sensitivity and specificity. Also, ANOVA methods were used to assess the impact of footwear, testing conditions (normal force, sliding speed and shoe angle) and all first-order interactions on ACOF measurements. A cube root transformation was performed on ACOF to achieve normality in residuals. In the case that the normal force or footwear-contaminant conditions were significant, post-hoc Tukey HSD tests were performed to determine which values were significantly different. For significant interactions involving footwear-contaminant conditions and a testing condition (e.g., normal force), post-hoc Tukey HSD test were performed to determine differences across the testing conditions (e.g., normal force) for each particular footwear condition.

Results:

The ACOF values obtained from the device for twelve testing conditions and nine footwear-contaminant conditions ranged from 0.01 to 0.27. The ACOF results were highly repeatable within condition with no standard deviations exceeding 0.01.

The human slipping experiments yielded 45 slips occurring across 124 exposures, leading to an overall slip rate of 36.3%. The slip rates for particular footwear-contaminant conditions ranged from 0% to 100%. The average (standard deviation) slip distance was 195 mm (97 mm) for slips and 8.8 mm (6.3 mm) for non-slips. The RCOF values taken during the dry control trials ranged from 0.14 to 0.28 with a mean of 0.20 and a standard deviation of 0.03.

The ACOF values were significantly influenced by the type of footwear and the testing conditions. Specifically, footwear ($F_{8,58}$ = 637.3, p<0.001), normal force ($F_{2,58}$ = 32.3, p<0.001), shoe angle ($F_{1,58}$ = 27.8, p<0.001) and sliding speed ($F_{1,58}$ = 6.2, p=0.016) influenced ACOF (Figure 3). Higher normal forces were associated with an increase in ACOF, increased shoe angle was associated with a decrease in ACOF, and increased sliding speed was associated with a decrease in ACOF. The only significant interaction effects were the interaction between footwear and angle ($F_{8,58}$ = 10.2, p<0.001); the interaction between footwear and normal force ($F_{16,58}$ = 15.8, p<0.001); and the interaction between angle and normal force ($F_{2,58}$ = 4.7, p = 0.013). Specifically, some footwear demonstrated an increasing trend in ACOF with increasing normal force (S1, S2, S4, S5, S6 and B1) whereas the ACOF for other footwear had no trend (Figure 3A). Similarly, an increased angle led to a decrease in ACOF for some types of footwear (S1 and S5) but did not have an influence on other shoes (Figure 3B). A larger shoe angle led to a reduction in ACOF, on average, at the lowest force (250 N) but did not have an effect, on average, at the higher forces (400 or 500 N).

Logistic regression results:

Overall, the difference between ACOF and RCOF (ACOF-RCOF) was negatively correlated with slip rate. Within each condition, the footwear with a slip rate of 100% (S3) tended to have one of the lowest ACOF-RCOF and one of the footwear designs with a slip rate of 0% (S6) tended to have the highest ACOF-RCOF (Figure 4). The S4 shoe had among the highest ACOF-RCOF values despite also having a high slip rate (67%). The relationship between the ACOF-RCOF value and slip rate for the remaining footwear types varied across testing conditions. For example, the slip rate of these 6 other footwear designs followed no discernable trend with ACOF-RCOF when 500 N, 0.3 m/s and 7° shoe angle was the test condition (Figure 4A). On the other hand, the slip rate decreased with increasing ACOF-RCOF for these 6 footwear types for most of the test conditions when a 13° shoe angle was used (Figure 4B).

The logistic regression analysis for all of the testing conditions reached statistical significance ($p<0.001$) (Table 2). Specifically, all of the tests revealed that an increase in ACOF-RCOF was associated with a reduction in slipping rate (Figure 5). The β_1 values (and odds ratios for an increase of 0.01 in ACOF-RCOF) varied between 9.12 (8.3%) and 18.48 (20.3%). An ACOF-RCOF increase of 0.01 was associated with a 12.0% and 15.1% reduction in slipping odds for the 400 N, 13°, 0.3 m/s and 500 N, 13°, 0.5 m/s tests, respectively. The regression for the F2913 standard (500 N, 7°, 0.3 m/s) predicted a reduction of 8.3% in slipping odds for each 0.01 increase in ACOF-RCOF.

The ROC analysis showed that AUC ranged from 0.699 to 0.748 across these tests (Table 2). Interestingly, the four testing conditions with the highest AUC were associated with an angle of 13° and four of the five testing conditions with the lowest AUC were associated with an angle of 7° (Table 2). AUC values varied significantly across the tests ($\chi^2_{11} = 41.3$, $p<0.001$). The post-hoc analyses revealed that one testing condition (500 N, 13°, 0.5 m/s) yielded a significantly higher AUC value ($p = 0.003$). Additionally, four other testing conditions (400 N, 13°, 0.3 m/s; 400 N, 13°, 0.5 m/s; 500 N, 13°, 0.5 m/s; 400 N, 13°, 0.3 m/s) yielded higher AUC values that did not quite reach statistical significance but had p-values below 0.05 (p-values of between 0.010 and 0.033) (Table 2). For the 500 N, 13°, 0.5 m/s test condition, an optimal balance between sensitivity and specificity was found for a cutoff of −0.123, which yielded a sensitivity of 71.1% and a specificity of 72.2% (Figure 6). The 400 N, 13°, 0.3 m/s test condition had an optimal balance between sensitivity and specificity at a cutoff of −0.156, which yielded a sensitivity of 62.2% and a specificity of 84.8% (Figure 6). In contrast, the testing parameters specified by ASTM F2913 yielded an AUC of 0.699, and an optimal sensitivity of 62.2% and an optimal specificity of 77.2% at a cutoff of −0.137 (Figure 6).

Discussion:

This study determined that models including the ACOF values measured with the STM 603 device and RCOF values measured during walking can predict slip outcomes. The ACOF measurements were dependent upon the testing conditions (normal force, shoe angle and velocity) and the quality of the resulting logistic regression models were significantly different. The testing conditions prescribed by ASTM F2913 (500 N, 7°, 0.3 m/s) achieved statistical significance but had the lowest AUC from the ROC curves of the conditions considered. One of the testing conditions (500 N, 13°, 0.5 m/s) was found to have a significantly higher AUC than the ASTM test method during post-hoc testing. Generally, the testing conditions with a higher shoe angle (13°) and one of the two higher force levels (400 N or 500 N) were associated with slightly higher AUC values than testing conditions with lower angles or lower forces. Updating the testing methods used by the STM 603 device, especially by incorporating a higher shoe angle, is warranted to improve the ability of ACOF results to predict slips.

Increases in ACOF-RCOF were associated with a reduced risk of slipping. This finding is consistent with previous research (Hanson *et al.* 1999, Burnfield and Powers 2006, Siegmund *et al.* 2006, Tsai and Powers 2008). Previous studies have quantified ACOF-RCOF coefficients (β_1) of between 12.9 and 54.7 (Hanson *et al.* 1999, Burnfield and Powers 2006, Siegmund *et al.* 2006, Tsai and Powers 2008). The present study found that the coefficient values (β_1) ranged from 9.12 to 18.48. Thus, the coefficient values reported in this study are similar to logistic models reported previously in the literature. The optimal accuracy in this study (76.6% based on the cutoff value identified by the gray ellipse in Figure 6) was similar to values previously reported by Blanchette and Powers (2015b) (74%). Complex interactions between the testing parameters and footwear were identified, which is supported by previous research that found complex interactions between testing parameters on ACOF values (Redfern and Bidanda 1994, Grönqvist 1995, Beschorner *et al.* 2007). Lastly, larger angles, lower normal forces and higher sliding speeds were associated with reduced ACOF values consistent with previous findings (Redfern and Bidanda 1994, Grönqvist 1995, Wilson 1996, Gronqvist *et al.* 2003, Beschorner *et al.* 2007). Thus, the current study further supports previously published findings that the difference between ACOF and RCOF is relevant to slipping but is dependent on the conditions used in testing ACOF.

The improvements in the predictive ability of the STM 603 by modifying test parameters were notable but not dramatic. Improvements in the AUC were observed to be approximately 0.05 between the under-shoe conditions used in the ASTM F2913 conditions and test conditions using a force of 400 N and a shoe angle of 13°. While no magic threshold exists for separating good from poor diagnostic tests based on AUC, guidelines from Hosmer et al. would suggest that the improved test methods (e.g., 400N, 13°,0.3m/s, AUC = 0.748) were in the center of the range that is considered “acceptable discrimination” whereas the ASTM F2913 methods (AUC = 0.699) were at the high end of the range that is considered “poor discrimination” (Hosmer et al. 2013). The magnitude of the improvement in AUC (~0.05) between the ASTM F2913 test and the modified set of parameters (e.g., 400N, 13°,0.3m/s) is similar to the improvements in AUC for other research studies that have been associated with substantial improvements in diagnostic performance (Imperiale et al. 2014). Other research studies that made comparisons across diagnostic tests have noted improvements in AUC of 0.09 to 0.3 (Nørgaard et al. 2014, Li et al. 2017). Thus, the improvements in AUC observed in this study could be considered important yet modest.

One of the footwear designs (S4) had a surprisingly high slip rate given its relatively high ACOF-RCOF (Figure 4). We assessed the influence of this footwear design on the results by reexamining the results, while excluding data from S4. When omitting data from S4, the coefficient values (β_1) values ranged from 22.1 to 52.5 (compared to a range of 9.12 to 18.48 when including S4). Furthermore, the area under the curve improved to a range of 0.811 to

0.884 when excluding S4 (as opposed to 0.699 to 0.748 when including the S4) across the test methods. Therefore, in the absence of this shoe, the discrimination for all tests would be considered "excellent" (Hosmer *et al.* 2013). When excluding shoe S4, there is an improvement of 0.07 between the ASTM F2913 (AUC = 0.817) test method and the improved test methods (400N, 13°, 0.3m/s; AUC = 0.884). Thus, modifying the test parameters appears to yield benefits even when excluding data from S4. Shoe S4 seems to be responsible for reducing the coefficient values and predictive discrimination in all of the models but does not influence the conclusion that predictive discrimination can be improved by modifying the test parameters. No clear reason is apparent for this aberrant shoe since it was similar to other shoes (S5 and S6). Notably, this shoe also had a surprisingly high ACOF when tested with another slip-tester device (Iraqi *et al.* 2018a). Therefore, the aberration of this shoe's performance from the rest of the data appears to be an anomaly as opposed to a behavioral fault of the STM 603 device.

The validation approach utilized in this study is largely consistent with recommendations by other researchers. Chang et al. argues that only ACOF tests with adequate biomechanical fidelity (i.e., mimicking the biomechanics of slipping) should be considered candidates for predicting slips (Chang *et al.* 2016). The testing conditions considered in this study were aimed to represent conditions that could be reasonably considered "biofidelic". Uncertainty remains regarding the precise biomechanical conditions that should be considered biofidelic. One complicating factor is that the under-heel dynamics during slips are transient and no slip tester has been developed that reproduces these time-varying dynamics. When walking on slippery level surfaces, the mean normal (vertical) forces vary between 130–300 N at slip start to over 500 N at peak slipping speed (Iraqi *et al.* 2018b); the sliding speeds vary between 0.4 and 1.0 m/s at heel contact (Cham and Redfern 2002b), 0.3 m/s at slip start (Albert *et al.* 2017) to over 1.5 m/s at peak slipping speed (Albert *et al.* 2017); and shoe angles have been reported between 18 and 30° at heel contact (Strandberg and Lanshammar 1981, Cham and Redfern 2002b, Chambers *et al.* 2003, McGorry *et al.* 2008, McGorry *et al.* 2010), between 15 and 24° at slip start (Albert *et al.* 2017, Iraqi *et al.* 2018b), and about 7° at peak slipping speed (Albert *et al.* 2017, Iraqi *et al.* 2018b). Thus, all of the testing conditions considered in this study are relevant to some portion of the slip and the testing conditions in this study could reasonably be considered as potential biofidelic candidates.

Prior research on footwear-floor tribology and the biomechanics of slipping may explain why a higher shoe angle provided better predictions of slipping. Of the five test conditions that reached significance or neared significance when comparing their AUC to the F2913 method, four of these test methods utilized the higher shoe angle. Recent research has indicated that the angle between the shoe and ground is approximately 15 to 24° at the moment that the foot starts slipping forward (Albert *et al.* 2017, Iraqi *et al.* 2018b). Thus, a higher shoe angle may be more representative of the state of the foot during the critical time of slip onset. Furthermore, shoe angle has a major impact on the measured ACOF (Grönqvist 1995, Beschorner *et al.* 2007, Moghaddam and Beschorner 2017). Changes in shoe angle lead to differences in contact area, which is correlated with hysteresis friction (Moghaddam and Beschorner 2017, Jones *et al.* 2018). Contact area can also influence the hydrodynamic pressures between the heel and the floor predicted by the Reynolds equation (Strandberg 1985, Chang *et al.* 2001b, Chang *et al.* 2008, Hemler and Beschorner 2017).

Thus, ACOF values taken with a higher shoe-floor angle may have led to better predictions of slipping because they resembled the state of the heel during the critical portion of slipping and had a major influence on the tribology phenomena during slipping.

The results of this study have important public health implications for preventing slip and fall accidents. First, the study indicates that the predictive ability of current testing conditions could be modestly improved by altering the test conditions. The interaction effects of shoe angle with footwear-contaminant conditions suggest that different types of footwear respond to changes in shoe angle in different ways. Since manufacturers use ACOF data to assess the performance of their footwear and guide design decisions, it is likely that updating this angle will guide footwear development to optimize tread designs for this angle (e.g., by beveling the heel at a greater angle) (Albert *et al.* 2017). Second, this study demonstrates that both the ASTM F2913 method as well as the STM 603 device operating under other testing conditions have utility in evaluating the traction performance of footwear even as alternative test methods are developed. It should be noted, however, that the predictive ability of the test methods presented in this study could theoretically be substantially improved given that the observed AUC values (0.699 to 0.748) were considerably lower than the upper limit for a diagnostic tool (1.000). Thus, further research into slip prediction and development of novel shoe traction testing technology is warranted.

This study has certain limitations that should be acknowledged. First, a limited number of footwear were included. While this study analyzed the largest sample of human slip results compared to slip measurement to-date, future studies are needed that include more footwear and subject testing. Second, the twelve test conditions (angles, forces and speeds) that were considered are just a small subset of the total condition set that is possible to test with the STM 603 device. Thus, considering a larger range of test conditions may be needed to pinpoint the precise conditions that best predict slips given the nonlinear effects that can sometimes occur between ACOF and testing conditions. Furthermore, test conditions that are unique to other testing devices were not considered. Thus, the results of the study should not be extended to other testing devices. Third, only one footwear size was considered in ACOF testing. More precise slip risk models may be possible by testing each size worn and then using personalized ACOF values based on the subject's shoe size. Fourth, our study utilized changes in RCOF values to exclude data in an attempt to reduce the influence of anticipation effects on our results. The exact cutoff used to assess anticipation could be reasonably debated and using different cutoffs might have a slight influence on the results. To assess this effect, this exclusionary criterion was removed and the statistical analyses were repeated. This reanalysis revealed that eliminating this exclusionary criterion did not have a substantial influence on any of the hypotheses tested. Lastly, the study only considered slips on a small sub-set of liquid-contaminated surfaces. It is unknown if these results extend to other liquid-contaminated surfaces (water), surfaces containing dry contaminants (i.e., flour), or ice.

In conclusion, this study determined that the STM 603 device was capable of predicting slips but that the predictions could be improved by updating the testing conditions. In particular, increasing the shoe angle to 13° is likely to increase the predictive ability of the device's results. It is believed that improving the testing conditions that are utilized by this device will guide improvements in footwear slip-resistance and prevent slip and fall accidents.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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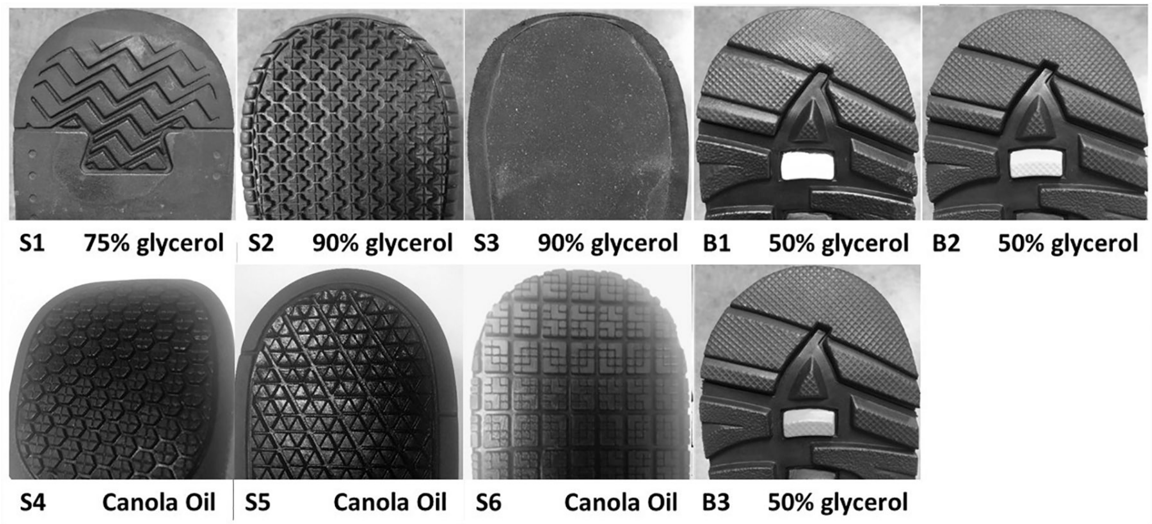

Figure 1:
Tread design of the heel for each of the footwear designs along with the liquid contaminant used with that footwear design. The three boots (B1, B2, and B3) had identical tread patterns but varying material hardness.

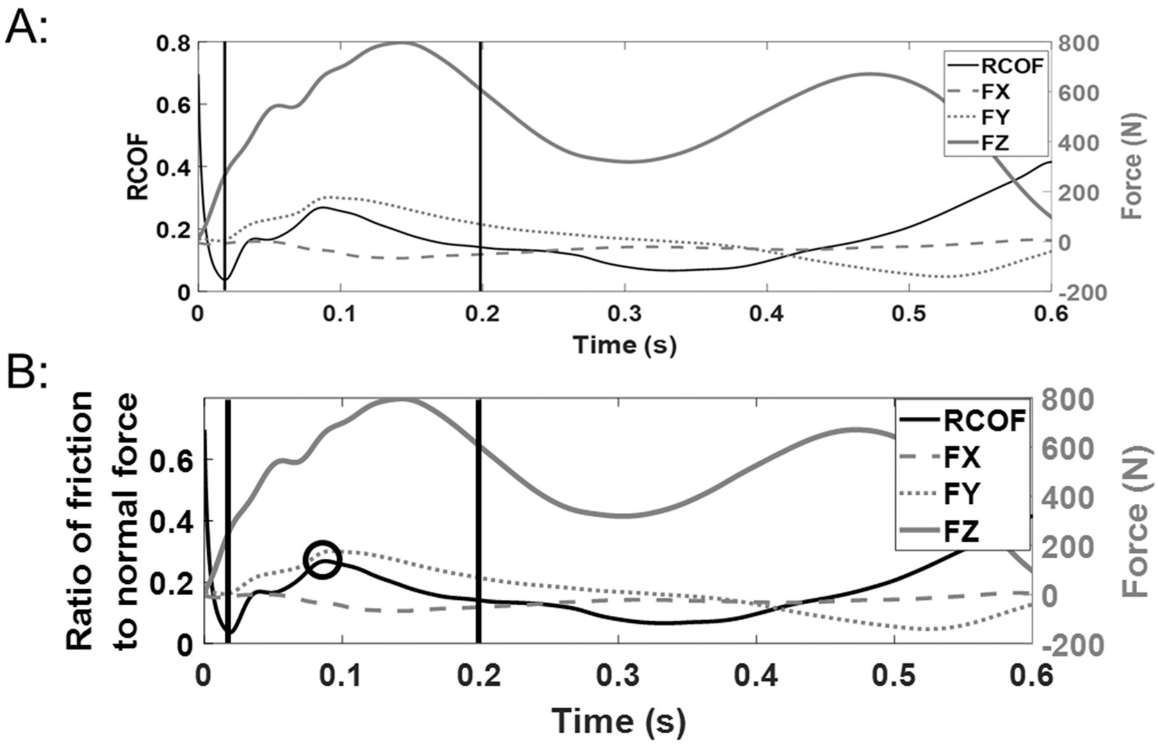

Figure 2:

A: Kinetic data from a dry trial (A) and kinematic data from a slipping trial (B) for a single representative subject. A: The time-series ratio of friction force to normal force is on the left y-axis (black line) and the ground reaction force data is on the right y-axis (gray lines). The data between the two vertical gray lines met all the criteria and the black circle represents the peak value within this time range selected as the RCOF value. B: Time-series heel position data is on the left y-axis (black lines) and sliding speed data is on the right y-axis (gray line). The first vertical line indicates the defined start of the slip and the second vertical line indicates the end of the slip. Slip distance was the resultant heel displacement between these two time points.

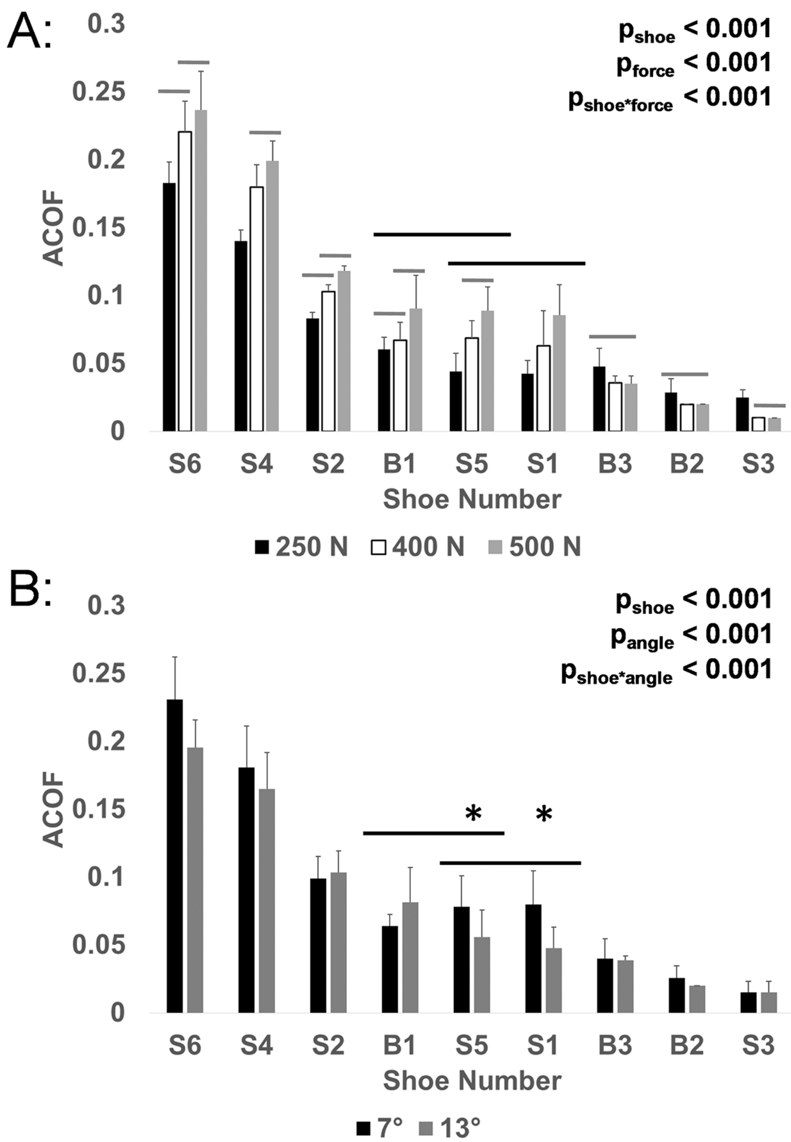

Figure 3:

Impact on ACOF of footwear (“shoe”)-contaminant condition; force (A); angle (B); the interaction between force and the footwear-contaminant condition (A); and the interaction between the angle and the footwear-contaminant condition (B). Error bars represent standard deviations across angles and speeds (A) or across forces and speeds (B). Footwear conditions connected by a horizontal black line were not significantly different. Forces connected by a horizontal gray line were not significantly different for a particular footwear condition (A). An asterisk indicates that the two angles were statistically significant for a particular footwear condition (B).

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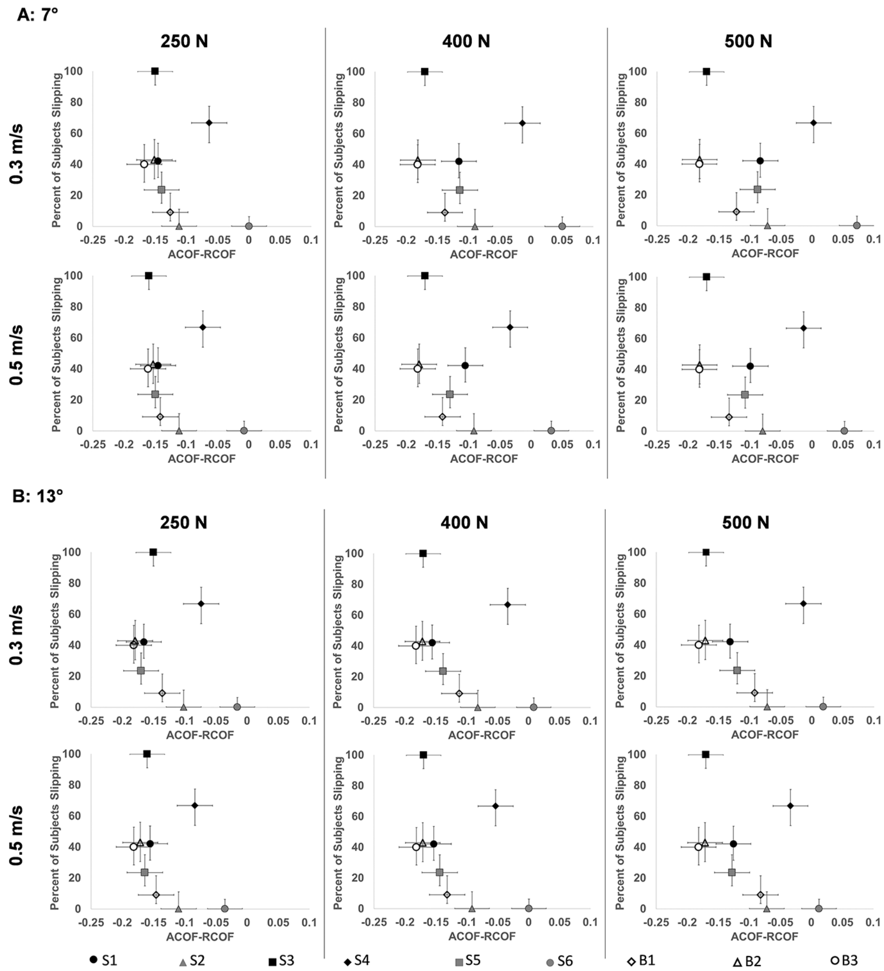

Figure 4:

Percent of subjects who slipped plotted against the mean difference between ACOF and RCOF for shoe angles of 7° (A) and 13° (B). Horizontal error bars represent the combined standard deviation of RCOF data across subjects and ACOF data across trials (i.e., $SD_{combined} = \sqrt{SD_{ACOF}{}^2 + SD_{RCOF}{}^2}$). Vertical error bars represent the 68% confidence interval (equivalent to 1 standard deviation) using the exact binomial method.

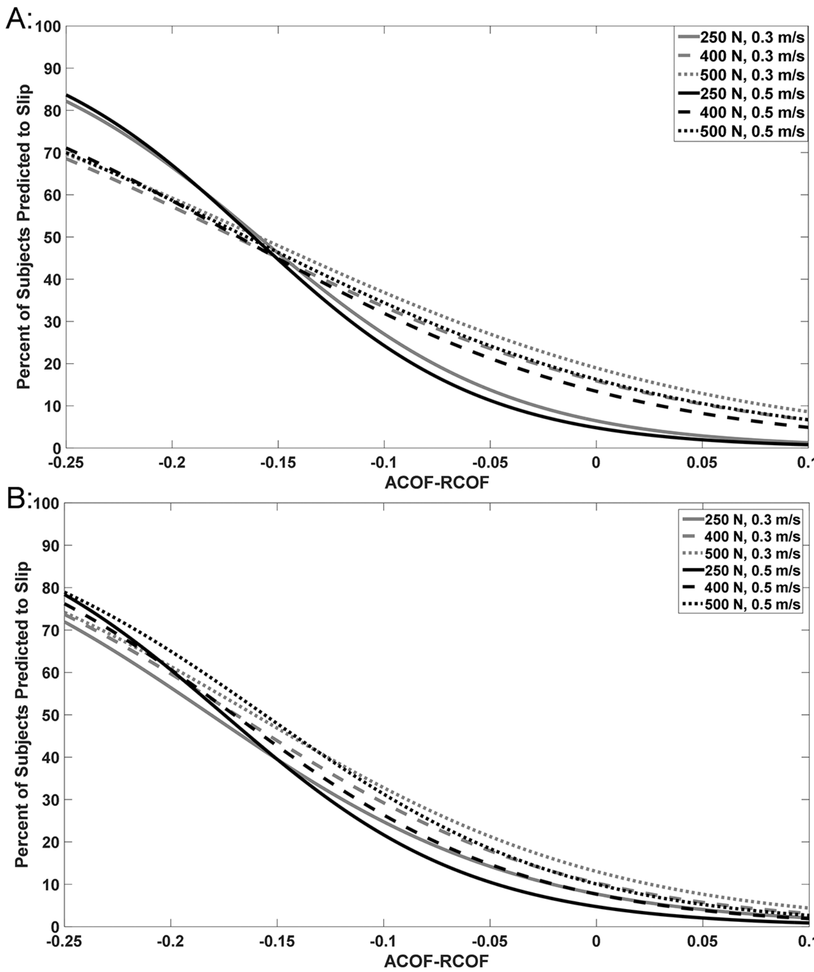

Figure 5:

Logistic regression models plotting the percent of subjects predicted to slip based on the difference between ACOF and RCOF when ACOF was measured with a shoe angle of 7° (A) and 13° (B). ACOF data collected with different forces is differentiated by different line types (250 N is solid, 400 N is dashed and 500 N is dotted). Gray lines indicate a sliding speed of 0.3 m/s and black lines indicate a sliding speed of 0.5 m/s.

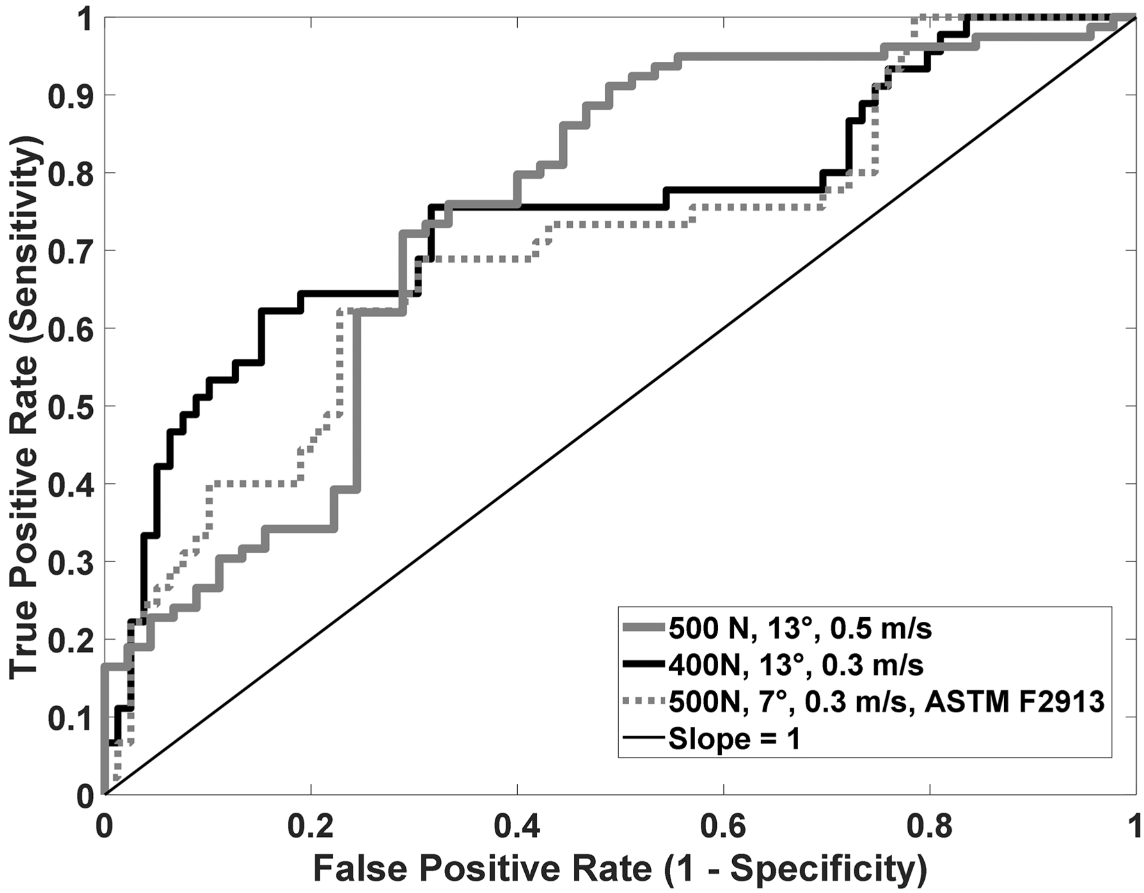

Figure 6:

Receiver operating characteristic (ROC) curve for 3 of the testing conditions (denoted in the legend). The point where the ROC curve deviates the most from the thin black line (i.e., the point that optimizes the balance between sensitivity and specificity) is identified with an ellipse for the 500 N, 13°, 0.5 m/s (gray) and 400 N, 13°, 0.3 m/s (black) test conditions and with a circle for the 500 N, 7°, 0.3 m/s test condition.

Table 1:

Number of subjects included in each test condition. Additional information for these shoe-contaminant conditions is available in Supplementary Table 1.

Shoe/boot	Contaminant	Number of subjects
S1 *‡	75% glycerol	19
S2	90% glycerol	8
S3‡	90% glycerol	10
S4	Canola oil	15
S5	Canola oil	17
S6	Canola oil	15
B1	50% glycerol	11
B2	50% glycerol	14
B3	50% glycerol	15

*Subjects wearing S1 were only exposed to this contaminant one time.

‡Shoes S1 and S3 were modified through mechanical abrasion of the surface.

Table 2:

Logistic regression coefficients, p-values, area under the curve (AUC), optimal sensitivity (Optim Sens) and optimal specificity (Optim Spec). Models are ranked based on the AUC with the highest value corresponding to the best rank.

Rank	Test Condition	β_0	β_1	p-value	AUC	Optim Sens	Optim Spec
1‡	400N, 13°,0.3m/s	2.16	12.76	<0.001	0.748	62.2	84.8
1‡	400N,13°, 0.5m/s	2.49	14.61	<0.001	0.748	62.2	83.5
3‡‡	500N,13°, 0.5m/s	2.19	14.04	<0.001	0.744	71.1	72.2
4‡	500N, 13°,0.3m/s°	1.90	11.81	<0.001	0.737	68.9	77.2
5	250N, 7°, 0.5m/s	2.99	18.48	<0.001	0.734	57.8	87.3
5	250N, 7°, 0.3m/s	2.68	16.81	<0.001	0.734	60.0	86.1
7	250N, 13°, 0.5m/s	3.00	17.16	<0.001	0.719	60.0	79.8
8‡	400N, 7°, 0.3m/s	1.67	9.78	<0.001	0.717	53.3	87.3
9	500N, 7°, 0.5m/s	1.64	9.94	<0.001	0.708	68.9	69.6
10	400N, 7°,0.5m/s	1.87	11.05	<0.001	0.706	53.3	87.3
11	250N, 13°, 0.3m/s	2.48	13.69	<0.001	0.702	53.3	81.0
12*	500N, 7°,0.3m/s°	1.45	9.12	<0.001	0.699	62.2	77.2

*Test conditions used in ASTM F2913

‡The AUC of this test method relative to the ASTM F2913 standard neared significance (0.0045<p<0.05)

‡‡The AUC of this test method relative to the ASTM F2913 standard was significantly different (p< 0.0045)