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Human Slip Assessment of Candidate Reference Surfaces for Walkway Tribometer Validation: An Update to Standard ASTM F2508

Reference

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ABSTRACT

Previous studies have reported on the concept of using human subjects to rank and differentiate walkway surfaces that vary in slipperiness. Surfaces identified as having different levels of slipperiness, based on the outcomes of human subject walking trials, are then used to validate tribometer slip resistance measurements. This concept was adopted in the development of ASTM F2508-11, *Standard Practice for Validation and Calibration of Walkway Tribometers Using Reference Surfaces*. Because of a depleting supply of the reference surfaces cited by ASTM F2508, new reference surfaces are needed. In this study, our objective was to assess new candidate reference surfaces to update the ASTM F2508-16, *Standard Practice for Validation, Calibration, and Certification of Walkway Tribometers Using Reference Surfaces*. One hundred and forty-eight human subjects walked across four ceramic-based tiles (E, F, G, and H) under contaminated conditions. Our results revealed that, consistent with our prior studies, human subjects were able to rank and differentiate surfaces according to slipperiness. Moreover, the surfaces evaluated in this study demonstrate characteristics that make them suitable replacements for the ASTM F2508 reference surfaces. Based on our findings, we recommend that ASTM F2508 be updated using surfaces E, F, and G and that surface G be considered a candidate to establish a slip resistance threshold for walking.

Keywords

walkway safety, tribometer, slips, slip resistance, available friction, reference standard, ASTM F2508

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Introduction

Walkway tribometers are often used to measure the available friction or slip resistance of a walkway surface to assess its safety. Previous reviews of the scientific literature have reported the large inter-tribometer differences that exist when measuring the available friction of the same surface. These differences necessitate that tribometer validity for evaluating pedestrian slip risk be assessed against reference surfaces established through human subject ambulation and slip studies. Our previous research[1,2] has reported on the use of two objective criteria to establish the validity of a given tribometer: (1) can the tribometer rank the available friction of different surfaces in the same order indicated by human subject results, and (2) can the tribometer statistically differentiate between surfaces with significantly different levels of human slip risk? Based on the results of Powers et al. 2010,[2] these criteria were adopted by ASTM International Committee F13 Pedestrian/Walkway Safety and Footwear in the development of standard ASTM F2508-11, *Standard Practice for Validation and Calibration of Walkway Tribometers Using Reference Surfaces*.[3] This standard has undergone several revisions, and the current version is ASTM F2508-16, *Standard Practice for Validation, Calibration, and Certification of Walkway Tribometers Using Reference Surfaces*.[4]

The premise of using standard ASTM F2508-16 is that tribometer validity is based on properly ranking and differentiating surfaces known to vary in slipperiness based on human subject testing. In the Powers et al. 2010 study,[2] 80 human subjects walked across 4 different surfaces (black granite, ceramic porcelain, vinyl composition tile, and ceramic) under wet conditions. The outcomes of those walking trials were recorded as the number of heel slips, toe slips, or non-slips on each surface. Subsequent statistical analysis revealed significantly different proportions of these slip outcomes among the four surfaces, thereby establishing a set of walkway surfaces that represented a continuum of slipperiness. Those four surfaces became part of the ASTM F2508 standard as reference surfaces A through D (Adjunct Reference Surfaces ADJF2508CS) and are available for purchase through ASTM International.

To build upon the framework established by our prior study[2] and solidify the long-term viability of the ASTM F2508 standard, there are several issues that need to be addressed. First, a single contaminant was not used on the walkway surfaces during the human subject testing. One of the surfaces (black granite) required the use of a surfactant (Triton X-100) in solution with distilled water to achieve a consistent contaminant film. For the remaining three surfaces, we opted to use only distilled water. The use of two different contaminants consequently made the testing procedure in the current ASTM F2508 standard more cumbersome to perform. Second, resilient flooring (vinyl composition tile) was selected to serve as one of the reference surfaces. Since 2011, ASTM International has stored the original supply of adjunct reference surfaces until purchased. Although the ASTM F2508 standard (section 7.4) limits the use of reference surfaces to 5 years from the date of purchase, the lifespan of vinyl composition tile in storage remains unknown. In addition, Committee F13 has been made aware that the supply of reference surfaces held by ASTM International is diminishing. Because the current reference surfaces are nontraceable, and given the aforementioned issues, there is an immediate need to identify new candidate reference surfaces.

The importance of ASTM F2508-16 to walkway safety cannot be understated. To date, this is the only walkway safety standard that addresses the validity of tribometer measurements based on peer-reviewed published human ambulation studies of slips on level walkway surfaces, and moreover was developed within the walkway safety community with consensus among multiple tribometer manufacturers. Therefore, the primary objective of the current study was to assess new candidate reference surfaces to update the ASTM F2508-16 standard. The secondary objectives of this study were to address the issues described above and identify candidate reference surfaces that (1) would maintain their surface characteristics over time and (2) could be procured in a large enough quantity to serve as reference surfaces for the foreseeable future.

Methods

SUBJECTS

One hundred and fifty-five subjects were recruited for this study. Five subjects were excluded for medical reasons (see the section "Procedures"), and two subjects were excluded because of their awareness of the contaminated floor condition (see "Procedures"). Therefore, data for one hundred and forty-eight subjects (52 males, 96 females) between the ages of 21 and 40 years (mean age 25.0 ± 3.0 years) were analyzed for this study. All subjects were healthy and capable of independent ambulation. Subjects who reported any orthopedic injury or medical condition were excluded from participation. Prior to testing, each subject signed an informed consent approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

WALKWAY SURFACES AND CONDITIONS

Prior to the commencement of this study, a survey of potential surfaces (over two dozen) was performed using two tribometer models validated to ASTM F2508-16,[4] a Mark IIIB (Slip-Test Inc., Atlanta, GA) and an English XL (Excel Tribometers LLC, Chesapeake, VA). The intent of this survey was to identify surfaces that represented a range of slipperiness, based on measured available friction, that could elicit varied human responses when walked upon under wet conditions. Four flat ceramic-based tiles were selected as walking surfaces: E—polished, F—glazed, G—matte, and H—matte (Table 1). Should these surfaces be adopted as reference surfaces in the revision of ASTM F2508, they will be available for purchase through ASTM International. The surfaces were labelled E through H to avoid confusion with the surfaces used in companion human subject tests[2] and the current reference surfaces A through D in the ASTM F2508-16 standard.[4] This nomenclature is consistent with a companion study quantifying tribometer variability,[5] although surface F in the prior study (Interceramic, Barcelona II, honed, light grey) is different from surface F in the current work. Surfaces E, G, and H are the same in both studies. Each tile was provided by a member manufacturer of the Tile Council of North America (TCNA). Each walkway surface consisted of the requisite tiles to create a 0.6 by 1.2-m rectangular panel that was embedded in the center of a 10-m walkway. The surrounding laboratory floor consisted of dry slip-resistant high-pressure laminate. To create a continuous contaminant film during the trials where subjects were exposed to the contaminated walkway surface, a 740-ml solution of 0.05 % sodium-laurel-sulfate (SLS) and distilled water was applied to each surface to avoid beading and improve wetting.

PROCEDURES

All testing was performed at the Jacquelin Perry Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. The temperature and humidity in the laboratory during testing were 70°F

TABLE 1
Walkway surfaces

Surface	E: Polished	F: Glazed	G: Matte	H: Matte
Color	OR01 Ivory	1500 Rainier	White	MS01 Daino Reale
Material	Porcelain	Ceramic	Porcelain	Porcelain
Finish	Polished	Glazed	Matte	Matte
Tile size	61 by 61 cm[a]	30 by 30 cm[a]	61 by 61 cm[a]	61 by 61 cm[a]
Style	Orvieto, Part # OR01 24241U	Sierra	Virtue, Part # AV261 24x24 UHT	Mars Stone, Part # MS01 24241P
Manufacturer	American Wonder Porcelain	Daltile	Crossville	American Wonder Porcelain

Note: [a] Manufacturer specifies the tile dimensions in imperial units, which have been converted here to metric.

TABLE 2

Subject characteristics; mean (SD)

Surface	E: Polished	F: Glazed	G: Matte	H: Matte
Age, yrs	25.3 (3.8)	23.8 (2.1)	24.9 (2.4)	26.1 (3.5)
Height, m	1.69 (0.11)	1.69 (0.09)	1.71 (0.10)	1.70 (0.10)
Weight, kg	65.7 (9.7)	66.7 (13.2)	67.1 (12.2)	68.6 (15.2)
Shoe size (US)	8.2 (1.7)	8.4 (1.8)	8.2 (1.9)	8.3 (1.8)
Females/males	25/12	23/14	24/13	24/13
Total, N	37	37	37	37

and 40 %, respectively. Consistent with our prior study,[2] subjects were randomly assigned to one of the four walkway surfaces (37 subjects per group), and they were only exposed to one surface and one walking trial with the contaminant present. The four groups were matched in terms of age, height, and weight (**Table 2**). Also consistent with our prior study, each subject was provided with a pair of Gibson-style shoes in their size. The soles of these shoes consisted of a smooth styrene butadiene rubber with a 75 Shore A hardness (Vibram USA, Brookline, MA). In general, and consistent with the Gibson-style, the shoe design consisted of a black leather upper with laces, enclosed heel and toe, and a small heel lift. Before each test session, the floor was swept for dust and both the floor panel and shoe soles were cleaned with 70 % isopropyl alcohol.

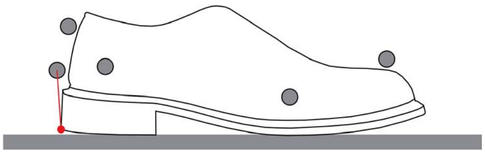
To ensure safety during all walking trials, subjects wore a fall-arresting harness (Miller Model 550-64; Franklin, PA) attached via a nonstretch lanyard (Miller Model FL11-1; Franklin, PA) to an overhead low-friction trolley that extended the length of the walkway. To avoid anticipatory gait changes to a potential perturbation (slip event),[6,7] procedures were enacted to limit participants' awareness to which trial the contaminant was present. Prior to walking trials, the lighting in the laboratory was reduced so that the illumination on the designated walkway measured approximately 43 lux (Extech EA31 light meter, Nashua, NH). This level of illumination ensured that the participants had ample lighting to walk safely while also providing additional concealment of the tile surface. In addition to the reduced illumination in the laboratory, subjects were instructed to walk with their head level and eyes focused on an eye-level target at the far end of the walkway. Subjects were permitted multiple practice walking trials to adjust to the harness system and reduced lighting conditions. In addition, these practice trials allowed the subjects to achieve a consistent target walking velocity of 1.4 m/s ± 5 %, which was monitored via photoelectric triggers placed at each end of the walkway. For a healthy adult, normal walking velocity has been reported to be 1.4 m/s.[8]

In between each trial, participants faced away from the walkway for 30 s and loud music was played. Once acclimated to the laboratory environment, kinematic data were obtained during nonslip walking trials on the dry walkway. A successful walking trial on the dry walkway was when the subject both walked at the target velocity and his/her foot landed wholly onto the 0.6 by 1.2-m floor panel. After obtaining four consecutive nonslip walking trials on the dry walkway, the 0.05 % SLS solution was applied to the walking surface during the following 30-s break. The contaminated trial was considered successful based on two criteria: (1) the foot landed wholly on the contaminated area, and (2) the subject was not aware in advance of the presence of the contaminant. Following the contaminated trial, participants were questioned on whether they had anticipated the slip or if they had seen the contaminant; an affirmative response to either question resulted in the subject being excluded from this study.

DATA ANALYSIS AND SLIP DEFINITION

In order to determine whether a slip occurred on a given walking surface, an 11-camera motion capture system (Qualisys AB, Gothenburg, Sweden) was used to capture kinematic data at 150 Hz. Because of software changes related to camera settings, kinematics for eight subjects were collected at 250 Hz, nine subjects at 100 Hz, and two subjects at 60 Hz. Subjects were instrumented with reflective markers placed bilaterally on the shoes (e.g., second toe, fifth metatarsal head, and 3-marker clusters on the heel counter) (**fig. 1**) and bilaterally on the subject (e.g., both lateral and medial malleoli). The outcome of each trial was classified as a nonslip, heel slip, or

FIG. 1 Diagram depicting marker location (grey dots) on the study footwear. To determine heel displacement, a virtual marker location (red dot) was determined from the dry trials to estimate the actual location of the shoe heel.



toe slip based on the displacements of the heel and toe during their interactions with the surface. Heel and toe displacements were determined from marker data for both dry and contaminated trials using a custom Matlab (R2018b, MathWorks, Natick, MA) script to account for intersubject differences in the location between the markers and the bottom of the shoe (fig. 1). A dry trial at the same walking speed as the wet trial was used to calculate the location of a virtual shoe marker that remained in the plane of the floor surface and minimized the horizontal translation of the heel relative to the surface between the time of heel strike and two frames before foot flat. This virtual marker was then used to determine the resultant anteroposterior and mediolateral displacements of the heel in the wet and dry trials. The resultant anteroposterior and mediolateral displacement of the toe marker was used directly to estimate toe displacement during push-off. Heel slips were defined as a 4-cm or more displacement of the heel marker following initial contact with the walking surface,[2] and toe slips were defined as 0.5-cm or more displacement of the toe marker. The outcomes of contaminated trials were confirmed visually for 83 trials where supplemental 30-Hz video was also recorded. Trials in which both a heel slip and a toe slip occurred were counted only as a heel slip (seven such dual slips occurred on Surface E only). The results from the dry trials were used to establish a baseline level of marker translation against which heel and toe displacement could be compared.

STATISTICAL ANALYSIS

To test for differences in the number and type of slip that occurred on the four surfaces, an omnibus chi-squared test for homogeneity was performed on a 4 by 3 (floor surface by slip type) contingency table at a significance level of $\alpha = 0.05$.[9] Post-hoc pair-wise comparisons were performed to further evaluate where specific differences occurred. For the pair-wise comparisons between surface E and any of the other surfaces, the comparisons included heel, toe, and nonslip data; for the pair-wise comparisons between the other three surfaces, the comparisons included only the toe and nonslip data because the analysis is undefined when both surfaces in a pair-wise comparison have zero heel slips.

Results

The human subjects' walking trials revealed significant differences in the slipperiness of the four surfaces (omnibus $C^2 = 91.9$, $p < 0.0001$; Table 3). All post-hoc pair-wise comparisons were significantly different except for surface G compared to surface H, as surface G produced 1 toe slip and 36 nonslip events, whereas surface H produced 37 nonslip events (Table 3). Follow-up analyses revealed that these inter-tile differences in slipperiness were robust, i.e., the significant differences in slip outcome among the walking surfaces were present when the threshold for a heel slip was lowered to 2 cm or the threshold for a toe slip was lowered to 0.2 cm. Out of the four surfaces, only surface E, polished porcelain, produced heel slips, with 43 % (16/37) of subjects experiencing a heel slip. Surface E was ranked as the most slippery by human subjects, with a combination of 30 heel and toe slips and only 7 nonslip events. The next slipperiest surface was surface F, glazed ceramic, eliciting 7 toe slips and 30 nonslip events. Consistent with our previous studies,[1,2] our ranking of walking surfaces is based on the premise that heel slips are potentially more injurious compared to toe slip or nonslip events; because of where these events

TABLE 3

Slip outcomes and the results of the post-hoc pair-wise comparisons

Surface	E – Polished	F – Glazed	G – Matte	H – Matte
Heel slips	16	0	0	0
Toe slips	14	7	1	0
Non-slips	7	30	36	37
Total N	37	37	37	37
Post-hoc tests				
E – Polished	…	$X^2 = 32.6$, $p < 0.0001$[a]	$X^2 = 46.8$, $p < 0.0001$[a]	$X^2 = 50.5$, $p < 0.0001$[a]
F – Glazed	…	…	$X^2 = 5.05$, $p = 0.025$[b]	$X^2 = 7.73$, $p = 0.0054$[b]
G – Matte	…	…	…	$X^2 = 1.01$, $p = 0.31$[b]

Note: [a] Post-hoc test includes heel, toe, and nonslips. [b] Post-hoc tests include only toe and nonslips.

occur within the gait cycle, heel slips are more likely than toe slips to be associated with falls when walking straight on level walkway surfaces.

Out of 37 subjects, 16 experienced a heel slip on wet surface E, and interestingly, 88 % (14/16) of those had maximum heel displacements greater than 10 cm (fig. 2). On wet surface F, two subjects had maximum heel displacements measuring 3.0 and 3.1 cm; these were not counted as heel slips based on the 4-cm threshold but were considered in our follow-up analysis (discussed below). During the contaminated walking trials, 11 subjects on surface E, 28 subjects on surface F, and 29 subjects on both surfaces G and H experienced maximum heel displacements of less than or equal to 1 cm. During the dry walking trials, 37 subjects on surface E, 34 subjects on surface F, 28 subjects on surface G, and 33 subjects on surface H experienced maximum heel displacements of less than or equal to 1 cm (fig. 3). Thus, there was a similar distribution of heel displacement on surfaces F, G, and H when dry or wet.

The maximum heel displacements observed among the four surfaces under both dry and wet conditions are presented in Table 4. The maximum heel displacement on surface E when wet was 80.3 cm, which was markedly above its maximum dry heel displacement of 1.0 cm. Conversely, on surfaces F, G, and H, the difference between maximum dry and wet heel displacements was marginal. Surface F produced a maximum heel displacement of

FIG. 2 Graph depicting the maximum heel displacement of all subjects on the four walking surfaces under wet conditions, ordered from greatest to least displacement. Heel displacements for surface E are displayed on the primary Y-axis (left) and heel displacements for surfaces F, G, and H are displayed on the secondary Y-axis (right).

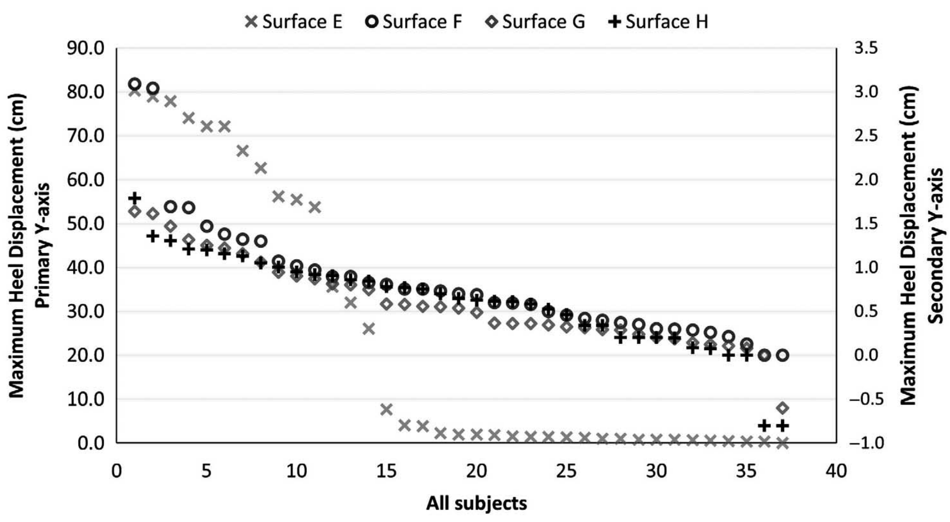


FIG. 3 Graph depicting the maximum heel displacement of all subjects on the four walking surfaces under dry conditions, ordered from greatest to least displacement.

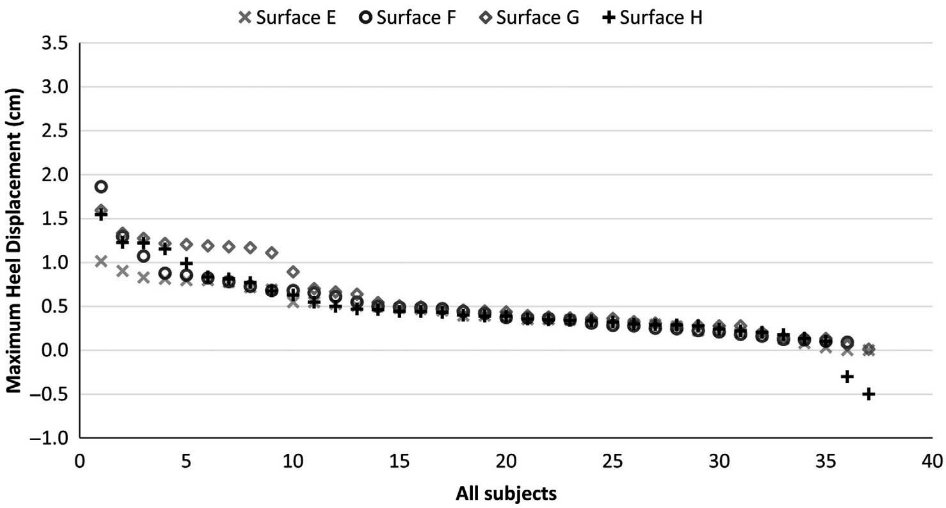


TABLE 4
Maximum heel displacements

Surface	E – Polished	F – Glazed	G – Matte	H – Matte
Dry, cm	1.0	1.9	1.6	1.5
Wet, cm	80.3	3.1	1.6	1.8

3.1 cm wet compared to 1.9 cm dry. The maximum heel displacements for surfaces G and H were essentially the same under dry and wet conditions, measuring 1.6 versus 1.6 cm and 1.5 versus 1.8 cm, respectively. The maximum heel displacement under dry conditions was less than 2 cm on all surfaces.

Discussion

The primary objective of the current study was to assess new candidate reference surfaces to update the ASTM F2508-16 standard. The results of the human subject testing revealed that the walking surfaces evaluated in this study represented a continuum of slipperiness, with the human subjects ranking and differentiating among three of them. Statistical differences in slip outcome were not observed between surfaces G and H. Therefore, two groups of three surfaces (E, F, G and E, F, H) were ranked and differentiated by the human subjects, making each group a candidate adjunct suite for the standard.

The results of this study highlight a transition in slip potential when walking on contaminated surfaces. More specifically, from surface G to surface H, a transition in human subject kinematics was observed from minimal toe slips (1/37 toe slips) to only nonslip events (37/37). Although these results were not statistically different, the trend suggests that surface G may lie close to the putative boundary between slippery and slip resistant flooring surfaces. In general, slips occur when the utilized friction (uCOF) of the ambulator exceeds the available friction provided by the shoe-floor interface.[10–17] Utilized friction, also known as required friction, is the friction force required to maintain motion without slipping[10,18] and is calculated from ground reaction forces in a laboratory setting. Utilized friction is generally highest in the late stance phase of gait (just before toe-off) as weight is being transferred off the trailing limb and onto the leading support limb. Toe slips occur when the uCOF during late stance is greater than the available friction provided by the shoe-floor interface. As previously discussed, toe slips are unlikely to lead to falls when they occur during straight and level walking. Therefore, the observation of a single toe slip on surface G marks an inflection point in the slip continuum, such that surface G could be considered as a candidate surface to establish a slip resistance threshold. This opinion considers feedback from the membership of Committee F13 and participants in the tribometer workshop[5] that surface H was qualitatively not as consistent a surface as surface G and exhibited characteristics (i.e., pitting, granular texture) not desirable for a reference surface. Given these concerns with surface H, and the strengths of surface G, we recommend that the new set of reference surfaces for standard ASTM F2508 comprise surfaces E, F, and G.

The secondary objectives of this study were to address the issues related to the long-term viability of the ASTM F2508 standard and to identify candidate reference surfaces that (1) would maintain their surface characteristics over time and (2) could be procured in large enough quantities to serve as reference surfaces for the foreseeable future. For this study, only ceramic-based, nonresilient tiles were chosen. These tiles do not possess any known surface treatments that are expected to degrade over time or be prone to appreciable wear from tribometer testing. Additionally, prior to this study, all the surfaces were procured in large enough quantities to serve as reference surfaces for the foreseeable future. The tiles were sourced through member-companies of the TCNA and are therefore traceable for future procurement if necessary. To address methodological disadvantages of the existing standard, a single contaminant of 0.05 % SLS solution was used, rather than two contaminants as in the current standard.[2] The use of 0.05 % SLS solution was chosen because it proved to be the lowest concentration of SLS that achieved a consistent film on the polished porcelain surface (surface E) in pilot testing. This concentration is also consistent with other standards related to measuring slip resistance (e.g., ANSI A326.3-2017 and ANSI A137.1-2019) and one of our goals with this research is to harmonize protocols across the walkway safety community. In addition, it is the authors' hope that future research explores how surface G from the current study compares to the minimum DCOF measurement described in ANSI A326.3, further harmonizing slip resistance standards.

The heel displacements observed across the four surfaces in this study were consistent with previously described slip kinematics. Redfern et al. 2001[19] previously reported on the slip distances associated with trial outcomes for level walking; slip distances were qualified into three categories, normal/micro-slip, slip/macro-slip, and fall. First, micro-slips were associated with normal shoe-floor interactions during walking and were generally considered to be heel slip distances of less than 1 cm. In the current study, although expected and observed on the dry surfaces, micro-slips were also observed during contaminated trials, with 11 subjects on surface E, 28 subjects on surface F, and 29 subjects each on surfaces G and H experiencing heel displacements of less than or equal to 1 cm. Second, heel slip distances on the order of a few centimeters were categorized as slip/macro-slips.[19] In the current study, the observed maximum heel displacement under dry conditions was less than 2 cm (maximum 1.9 cm on surface F) on each of the four surfaces, indicating that 2 cm served as a boundary between dry and wet outcomes and represented normal shoe-floor interactions, and should be categorized as micro-slips. Our observations of heel displacement during dry surface conditions in conjunction with the descriptions by Redfern et al. led us to conduct a follow-up analysis adjusting the heel slip threshold from 4 to 2 cm (see below). Third, slip distances exceeding 10 cm have been associated with a risk of falls.[19,20] Based on our results, surface E, in which 14 out of 37 subjects experienced heel displacements of greater than 10 cm when wet, would be considered a potentially hazardous surface to walk on when wet.

We performed two follow-up analyses using the same statistical test but varied the threshold for the heel and toe slip distances. Our first follow-up analysis evaluated 2 cm as a heel slip threshold. Using the 2-cm criteria, surface E produced 18 heel slips, 14 toe slips, and 5 nonslips, whereas surface F produced 2 heel slips, 6 toe slip, and 29 nonslips. Neither surfaces G nor H were affected. Lowering the heel slip threshold to 2 cm and keeping the toe slip threshold at 0.5 cm did not affect the outcome of our analysis. We performed a second follow-up analysis adjusting the toe slip threshold to 0.2 cm. With the heel slip threshold at 4 cm, only the results on surface E were affected by this adjustment, producing 16 heel slips, 15 toe slips, and 6 nonslips, which was 1 additional toe slip compared to the original analysis. When adjusting both heel and toe slip criteria to 2 cm and 0.2 cm, respectively, the results were again similar to our original analysis and still statistically significant. Surface E produced 18 heel slips, 15 toe slips, and 4 nonslips, whereas surface F produced 2 heel slips, 6 toe slips, and 29 nonslips. The fact that minimal changes in slip outcome were observed when modifying the slip threshold criteria reinforces our choice of slip threshold values and the fitness of these surfaces as candidate reference surfaces.

Although ASTM F2508-16 is critical to the evaluation of floor slipperiness, additional guidance is needed as it pertains to evaluations of walkway safety. In conjunction with the tribometer and surface variability results reported earlier,[5] the results from this study are currently being evaluated by Committee F13 in the development of additional walkway safety standards. Such standards include a standard practice for evaluating the homogeneity of reference surfaces, a standard practice for correlating tribometer measurements to human slip risk using reference surfaces, a standard practice proposing target safety thresholds for available friction, and a rating system for the available friction of flooring. The development of these additional standards is the next step to increasing walkway safety and to reducing the incidence of slip-related injuries, which are part of Committee F13's mission to provide meaningful and practical standards.

This study has several limitations that need to be acknowledged. First, as in the Powers et al. 2010 study,[2] only one shoe was evaluated. Although our findings do not incorporate the potential effects of different shoe designs, outsole tread patterns, or materials, we believe that the standardized shoe utilized in the current study is relevant to available products in the marketplace. A second limitation is the use of 0.05 % SLS solution as a single contaminant. Although this contaminant may not represent all potentially slippery walkway conditions, it does allow for easy comparative testing (i.e., versus water) whether in a laboratory setting or the field. Additionally, we did not incorporate a load cell into the harness setup. Such data would have been potentially beneficial to assess fall risk when ambulating on the subject surfaces, compared with heel displacement alone. Lastly, although the results of the current study are robust and strongly indicate that surface G is informative with respect to slip risk, our study methodology does not address all the factors related to slip risk including (i.e., walkway slope, footwear, activity, and age). Thus, the findings and conclusions of the current study may not be applicable to all situations where slips may occur.

Summary

The current study found significantly different levels of slipperiness between three of the four ceramic walkway surfaces when traversed by human subjects ambulating at normal walking speeds. These results indicate that surfaces E, F, and G can be used to update the reference surfaces associated with standard ASTM F2508-16. In conjunction with the results reported in our earlier tribometer variability study, the results from this study are currently being evaluated by Committee F13 in the development of additional walkway safety standards.

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CONFLICT DISCLOSURE

All authors are forensic consultants who investigate slip-related accidents. MGB is the Chairman of the ASTM Research Subcommittee F13.40 and Secretary of Committee F13. JLC is the majority owner of Verum Biomechanics and a member of Committee F13. JRB is the majority owner of Semper Scientific and Past-Chairman of Committee F13. BR is a member of Committee F13. BSE is current Chairman of the ASTM Committee F13 on Pedestrian/Walkway Safety & Footwear, which is the committee responsible for the F-2508-16 standard. GPS is a minority shareholder of MEA Forensic and a director.

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