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Assessment of Walkway Tribometer Readings in Evaluating Slip Resistance: A Gait-Based Approach

ABSTRACT: The purpose of this study was to assess the viability of using slip risk (as quantified during human subject walking trials) to create a reference standard against which tribometer readings could be compared. First, human subjects ($N = 84$) were used to rank objectively the slipperiness of three different surfaces with and without a contaminant (six conditions). Second, nine tribometers were used to independently measure and rank surface slipperiness for all six conditions. The slipperiness ranking determined from the walking trials was considered the reference against which the tribometer measurements were compared. Our results revealed that only two of the nine tribometers tested (Tortus II and Mark III) met our compliance criteria by both correctly ranking all six conditions and differentiating between surfaces of differing degrees of slipperiness. These findings reinforce the need for objective criteria to ascertain which tribometers effectively evaluate floor slipperiness and a pedestrian's risk of slipping.

KEYWORDS: forensic science, tribometer, walkway safety, coefficient of friction, slip resistance

Tribometers are mechanical instruments that purport to measure the slip resistance of walkway surfaces. These devices are used in many industries including flooring, floor coating, and shoe to test product safety. In addition, tribometers are used in the property insurance and forensic-science communities to identify the causes and interventions for slip-and-fall events and claims. Currently, eight ASTM standards exist for six different tribometers and about 30 portable tribometers are available commercially (1–3). These tribometers operate using a range of mechanical designs from simple nonimpact drag sleds to more complex dynamic devices that attempt to simulate foot contact.

While many manufacturers claim that their tribometers can predict the probability of safe human ambulation on a walkway surface, numerous studies have shown that different tribometers yield different measurements of friction for the same flooring material (4–14). These friction differences approach an order of magnitude in some cases (5,9) and are often pronounced in the presence of a contaminant (15). These large intertribometer differences suggest that the value obtained from a given tribometer may or may not represent a measure of a pedestrian's risk of slip: a fact that potentially undermines the validity of all tribometers. Thus, objective criteria are needed to ascertain which tribometers effectively evaluate floor slipperiness and a pedestrian's risk of slipping.

In addition to having properties such as high repeatability (precision between device measurements with the same operator) and reproducibility (precision between device measurements from different operators), a tribometer should be able to rank correctly the slipperiness of different surfaces (Criteria 1) and differentiate between surfaces of differing degrees of slipperiness (Criteria 2). If a tribometer satisfies these compliance criteria, then a threshold slipperiness value for that tribometer has meaning, even if its absolute slipperiness value is not equal to or even linearly correlated to friction.

To determine whether a tribometer meets the above criteria, a series of surfaces of known slipperiness are required to function as reference standards against which tribometer readings can be compared. Unfortunately, no mechanical test to compute surface slipperiness relevant to human ambulation has been universally accepted. To resolve this problem, some researchers have used humans to evaluate subjectively the slipperiness of various combinations of floors, footwear, and contaminants by rubbing their shoe over a set of surfaces (16–21). Other researchers have recommended that dynamic human subject tests be used (22–24). As tribometers are ultimately tools to assess surface slipperiness for human locomotion, there is face validity to using the incidence of slip from human subject walking trials to quantify the relative slipperiness of different surfaces. Although this method does not quantify absolute slipperiness, it provides a potential means of validating tribometer readings over a range of slipperiness levels associated with slip events.

To date, only two studies have attempted to relate tribometer measurements to actual risk of slipping. Hanson et al. (23) created a gradient of available coefficient of friction (COF) to evaluate the relationship between tribometer measurements and actual slips with human subjects while descending a ramp. To create a gradient of slip resistance, the ramp angle and the application of contaminants to the walking surface were varied. While these authors were able to demonstrate that friction values obtained from a programmable slip resistance tester (PSRT) could be used to predict slip events, it should be noted that gait biomechanics while descending a ramp differs significantly from level walking (25).

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Therefore, the results of this study are difficult to extrapolate to slips on level surfaces. Similarly, Kulakowski et al. (12) correlated the measurements of one tribometer (NBS-Brungraber) to the results of human walking slip trials. These authors reported that 79% of slip events could be predicted based on knowledge of the subjects' utilized friction during walking and the friction values from the tribometer. A limitation of the studies conducted by Hanson et al. (23) and Kulakowski et al. (12) is that small sample sizes were utilized in each ($N = 5$), thereby limiting the generalizability of the results to the entire population.

Given the need for additional research in this area, the goal of this study was to assess the viability of using slip risk (as quantified during human subject walking trials) to create a reference standard against which tribometer readings could be compared. To achieve this goal, we conducted a two-part study. First, human subject slip events during walking were used to rank objectively the slipperiness of a suite of three different surfaces with and without a contaminant (six conditions). Second, nine tribometers independently measured and ranked the surface slipperiness for all six surface conditions. The human subject and tribometer rankings were then compared using the two criteria described above.

Methods

Human Subject Testing

Subjects—Eighty-four subjects (42 males, 42 females) between the ages of 22 and 38 years (mean age 25.9 ± 3.8 years) were recruited for this portion of the study. All subjects were healthy and capable of independent ambulation. Subjects who reported any orthopedic injury, medical condition, or pregnancy were excluded. Before testing, each subject signed an informed consent approved by the Institutional Review Board of the University of Southern California.

Floor Surfaces and Conditions—Three flat smooth surfaces were tested in both a dry and wet condition: a high-pressure laminate (HPL), which is a common high-density fiberboard flooring material; polytetraflouroethylene, which is a low-friction plastic polymer more commonly known as Teflon® (DuPont, Wilmington, DE); and an acetal material, which is a low-friction plastic polymer commonly referred to as Delrin® (DuPont). Each surface consisted of a $2' \times 4'$ rectangular section embedded near the middle of a 10 m walkway. For the wet condition, sufficient water was applied to the surface to create a continuous film. A nonionic surfactant, Triton X-100 (Gallade Chemical, Santa Ana, CA), was mixed into the water (five drops/250 mL) to improve wetting and minimize the amount of water needed.

Procedures—All testing was performed at the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. The temperature and humidity in the laboratory at the time of testing were 70°F and 34%, respectively.

To rank the slipperiness of the different surfaces objectively, subjects were randomly assigned to walk across one of the six floor surface conditions (14 subjects per group). To ensure a balanced gender distribution within each group, males and females were randomized separately. The six groups were similar in terms of age, height, and weight (Table 1).

To control for the influence of footwear, subjects were provided a pair of Oxford-style shoes in their size. The soles of these shoes consisted of a smooth styrene butadiene rubber (SBR) with shore A hardness of 75 (mid-range). This soling represented the most common shoe bottom material used globally in the year 2001 (William Ells, Quabaug Corp., personal communication). Before each test session, the floor was swept for dust and both the floor panel and shoe soles were cleaned with 70% ethanol solution.

All subjects wore a fall-arresting body harness attached to an overhead low-friction trolley that extended along the length of the walkway. Subjects first performed three to six nonslip walking trials, followed by a single trial in which the floor panel of interest was inserted into the walkway. Subjects were instructed to walk briskly for all trials. The average walking velocity for all subjects was 2.18 ± 0.13 m/sec as determined by photoelectric light switches. Walking speed did not vary between the six groups (Table 1).

As awareness of a potential slip and prior slip experience can generate alterations in human gait (26–28), special attention was paid to minimizing these effects. To reduce awareness of which trial contained the test surface, subjects left the room for a similar period of time between all trials (*c.* 2 min). Subjects also wore goggles with the lower half blacked out and were instructed to look at a spot on the far wall as they traversed the walkway. Lighting in the laboratory was decreased to minimize reflections from the wet surfaces, and a "spotter" at the far end of the walkway gave the appearance that the test surface was near the end rather than the middle of the walkway. To eliminate the effect of prior experience, subjects were exposed to their assigned test surface only once.

Slip Definition During Walking—Immediately following each walking trial, subjects were asked whether they perceived a slip. If so, they were then asked whether it was a heel or toe slip, and where along the walkway the slip occurred. To confirm objectively whether a slip occurred, an eight-camera (120 Hz) Vicon Motion Analysis System (Oxford Metrics Ltd., Oxford, UK) was used to record the position of reflective markers (25 mm spheres) placed on the heel and the second metatarsal head regions of the shoes. Heel slips were defined as 10 mm or more of anterior translation of the heel marker during the loading or early midstance phase of the gait cycle. A toe slip was defined as the presence of a negative (posterior) velocity of the toe marker before toe off. In all cases, the video data agreed with the subject's perception of a slip.

Tribometer Testing

Tribometers—Nine tribometers were used to measure the COF of the six surfaces (Table 2). Each tribometer was operated by an

TABLE 1—*Subject characteristics/mean (SD).*

Surfaces	Dry HPL	Dry Delrin®	Dry Teflon®	Wet HPL	Wet Delrin®	Wet Teflon®	Average
N	14	14	14	14	14	14	84
Age (years)	27.7 (4.0)	25.4 (2.6)	25.4 (2.8)	24.5 (2.5)	26.9 (5.0)	24.6 (2.3)	25.8 (3.5)
Height (cm)	171.1 (6.9)	171.2 (9.6)	171.1 (10.3)	168.3 (6.3)	170.4 (5.8)	170.8 (8.2)	170.5 (7.8)
Weight (kg)	69.9 (11.1)	65.5 (12.0)	71.8 (17.5)	67.5 (14.4)	67.4 (12.5)	68.3 (10.3)	68.4 (13.0)
Velocity (min/sec)	2.19 (0.08)	2.19 (0.19)	2.16 (0.18)	2.20 (0.11)	2.16 (0.12)	2.20 (0.11)	2.18 (0.13)

HPL, high-pressure laminate.

TABLE 2—*Tribometer name, type, and test foot material.*

Device	Operating Principle	Test Foot Material/Size
Horizontal pull slipmeter* (HPS)	Drag sled—motor pulled	Neolite® Test Liner† (NTL) (3) 13 mm diameter
C 1028‡	Drag sled—manually pulled	NTL 76 mm × 76 mm
Tortus II§	Drag sled—motor driven	Four S rubber¶ 9.5 mm diameter
Universal walkway tester‖ (UWT)	Drag sled—motor driven	NTL 28 mm × 28 mm
Sigler Pendulum**	Pendulum	NTL 38 mm × 38 mm
Wessex Pendulum††	Pendulum	Four S rubber 76 mm wide
Mark II‡‡	Articulated strut—gravity driven	NTL 76 mm × 76 mm grooved§§
Mark III‡‡	Articulated strut—spring activated	NTL 76 mm × 76 mm grooved§§
English XL¶¶	Variable incidence—pneumatically driven	NTL 32 mm diameter

*Developed by Irvine/Liberty Mutual, no longer manufactured.
†Smithers Scientific Services, Akron, OH.
‡No specific manufacturer.
§Severn Science Limited, Bristol, UK.
¶Standard simulated shoe sole, developed by Rubber & Plastics Research Association UK.
‖National Floor Safety Institute, Southlake, TX.
**Developed by Percy Sigler and National Bureau of Standards, no current manufacturer.
††Wessex Engineering Ltd., UK.
‡‡Slip-Test, Spring Lake, NJ.
§§Based on manufacturer's recommendations grooves were cut into test foot approximately 3 mm deep, 1.5 mm wide with lands 5 mm across.
¶¶William English Inc., Alva, FL.

experienced user of that device, and testing was performed according to the manufacturer's instructions or applicable standard. A second individual recorded the tribometer test results, while a third individual oversaw the testing protocol to ensure consistent technique and correct recording. The value measured by each tribometer was assumed to represent the COF measured by that tribometer and no distinction was made between measurements of static, transitional, and dynamic COF.

Procedures—Tribometer testing was conducted first on the three dry surfaces and then on the three wet surfaces. Test order was randomized separately within the dry and wet surfaces. The same solution and wetting protocol used in the human subject tests was used for the tribometer tests. When testing wet surfaces, each tribometer's test foot was dried thoroughly before testing the next wet surface. For each surface condition, the COF was measured four times: once in each of four orthogonal directions, i.e., at 0, 90, 180, and 270° relative to the longitudinal axis of the walkway.

Data Analysis

Each human walking trial over one of the six test surfaces was classified as a No Slip, Toe Slip, or Heel Slip. To test for differences in the type of slip (no, toe, or heel) that occurred on the six surfaces, a χ^2-test for homogeneity was performed on the 6×3 (floor condition × slip type) contingency table. *Post hoc* analyses were then performed using simple 2×3 χ^2 comparisons to identify homogeneous groups of surfaces (i.e., surfaces that the walking tests did not identify as being significantly different).

To test for differences between the measured friction values for each surface, the mean and standard deviation of the friction values for each tribometer/surface combination were first calculated. For each tribometer, a one-way analysis of variance (ANOVA) was used to determine whether significant differences were present between the six surfaces. *Post hoc* tests were run using a Fischer least significant difference (LSD) test to identify both homogeneous groups of surfaces and surfaces that were significantly different from one another according to that tribometer.

The omnibus χ^2 analyses was evaluated nondirectionally at a significance level of $\alpha = 0.05$. The significance levels for the nondirectional *post hoc* χ^2-tests were adjusted for the number of *post hoc* comparisons using a Bonferroni adjustment. The significance level for each ANOVA was $\alpha = 0.05$ and was not adjusted because the number of tribometers chosen for the study should not influence whether or not a specific tribometer identified the slipperiness of a specific pair of surfaces as significantly different.

Comparison of Human Subject and Tribometer Ranking—The slipperiness ranking determined from the walking trials was considered the reference against which the tribometer measurements were compared. The results of the tribometer measurements were then compared with the gait-based ranking of surface slipperiness using two criteria: (1) Did the tribometer measurements correctly rank the slipperiness of the different surfaces? (2) Did the tribometer measurements differentiate between surfaces with significantly different levels of slipperiness? Criteria 2 could only be applied to surface conditions that generated a combination of no, toe, and/or heel slips. It could not be applied to distinguish between surfaces that generate either no slips or all heel slips.

Results

The results of the human subject walking trials are presented in Table 3. Dry HPL, dry Delrin®, and wet HPL did not produce any slips and were characterized as being "not slippery" (not slippery group). Although wet Delrin® and wet Teflon® produced 10 and 13 heels slips, respectively, one was not more slippery than the other ($p = 0.77$) and thus both were characterized as being "very slippery" (very slippery group). Dry Teflon®'s mix of no slips and toe slips was more slippery than the three surfaces in the not slippery group ($p < 0.0001$) and less slippery than the two surfaces in the very slippery group ($p < 0.005$). The intermediate level of slipperiness demonstrated by dry Teflon® was therefore designated "slippery" (slippery group).

The distinction between the very slippery category containing primarily heel slips and the slippery category containing primarily toe slips was based on the fact that toe slips were interpreted as less ominous for the walker because of where they occur in the gait cycle. For example, toe slips take place in late stance as weight is being transferred to the contralateral (i.e., forward) limb. In contrast, heel slips occur in early stance when weight is be transferred to the lead limb. Therefore, a heel slip results in forward acceleration of the weight-bearing limb, which results in a

TABLE 3—*Number of slip events on the six surfaces.*

Surfaces	No Slips	Toe Slips	Heel Slips	Group
Dry HPL	14	0	0	Not slippery
Dry Delrin®	14	0	0	
Wet HPL	14	0	0	
Dry Teflon®	6	8	0	Slippery
Wet Delrin®	2	2	10	Very slippery
Wet Teflon®	0	1	13	
Total	50	11	23	$N = 84$

HPL, high-pressure laminate.

more unstable situation (i.e., the base of support is moving away from the body center of mass).

All nine tribometers measured significantly different friction values between at least some of the surfaces ($p < 0.0001$; Table 4). *Post hoc* testing revealed that the English XL discriminated all six surfaces, whereas the Wessex, Sigler, horizontal pull slipmeter (HPS), and universal walkway tester (UWT) resolved only four distinct friction levels among the six surfaces (Table 4). Across all tribometers and surfaces, friction measurements varied from a low of 0.06 ± 0.02 for the English XL on wet Delrin® to a high of 2.06 ± 0.28 for the Tortus II on dry HPL. Within the six surfaces, the most consistent range of friction values (0.26–0.48) was observed on dry Teflon® and the most varied range of friction values (0.66–2.06) was observed on dry HPL. A comparison of the tribometer measurements of friction to the gait-based ranking of surface slipperiness showed that two tribometers (Tortus II and Mark III) met our two criteria by correctly ranking the surfaces and being able to differentiate between surfaces of different degrees of slipperiness (Table 4). Four tribometers (Mark II, English XL, Wessex, and Sigler) satisfied criteria 2 and missed fulfilling criteria 1 by reversing the ranking order of two surfaces (Table 4).

Three tribometers (C 1028, HPS, and UWT) were unable to distinguish a difference between wet HPL and wet Delrin®, which were two surfaces that demonstrated significant differences in the risk of slip in the walking trials. These three tribometers did not meet either of the compliance criteria (Table 4).

Discussion

Tribometers are routinely used to assess the safety of pedestrian walkway surfaces. The importance and need for developing a biomechanical-based test method for evaluating the validity of tribometers has been recognized previously by investigators and has been gaining momentum within consensus standards organizations with an interest in walkway and footwear safety (23,29,30). Our experimental protocol demonstrated that a gait-based system can be used to create reference standards against which tribometer measurements can be compared.

The results of our tribometer measurements were consistent with the conclusions of previous studies in that different tribometers give varied COF values for the same surface (4–14). For example, wet Delrin® was categorized as being very slippery because of its ability to cause 12 of 14 subjects to slip; yet, the tribometers measured a range of COF from 0.06–0.69 for this surface. This extremely wide range underscores the impossibility of ascribing to a floor surface a single number to indicate its potential for causing a slip, a practice all too common in the standards writing process in the field of walkway and product safety. Unless all tribometers mimic the critical biomechanical parameters between the sole bottom, contaminant, and floor at heel strike, COF values will continue to be highly dependent on the test method used.

The wide range of COF values is no surprise, given the various operational principles for the selected tribometers (Table 1), not to mention, no tribometer has yet been developed that accurately models the kinematics and kinetics of the foot–floor interaction. The "classic" laws of friction formulated in the 17th century stated that COF is independent of contact area and velocity; however, these laws are not obeyed by either rubber polymers from which most tribometer test feet are constructed or the materials commonly used in flooring (31). In addition, the magnitude of the load, loading rate, pressure, and time of contact between two surfaces also influence COF results in the presence of rubber and plastic polymers. Chang et al. (32) provide an excellent review of such friction mechanisms during the measurement of slipperiness.

In the current study, only two of the nine tribometers tested (the Tortus II and Mark III) met our compliance criteria by correctly ranking all six conditions and differentiating between surfaces of differing degrees of slipperiness as established by the walking trials. The Tortus II is a drag sled-type tribometer whose friction slider is held in contact with the floor surface under a fixed load. The self-propelled machine moves forward at a constant velocity and the deflection of the friction slider is measured by a strain gauge. The device averages the surface's COF over a 20-cm distance. One noteworthy exception to the Tortus' ability to meet our compliance criteria was the high COF (2.06) and standard deviation (0.28) computed from its four measurements on the dry HPL. High COF results are not unusual with this device on certain dry surfaces. The phenomenon is likely explained by an affinity or adhesion between the device's test foot made of 4S rubber (Rubber & Plastics Research Association, UK) and the dry HPL tile.

The overall performance of the Tortus II was in direct contrast to the performance of the three other drag-sled tribometers (HPS, UWT, and C 1028), which failed to meet either of our criteria for a

TABLE 4—*Coefficient of friction for the six surfaces measured and the criteria met by the nine tribometers.*

Group	Surface	Tortus II	Mark III	Mark II	English XL	Wessex	Sigler	C 1028	HPS	UWT
Not slippery*	Dry HPL	2.06 (0.28)	0.67 (0.03)	0.80 (0.01)	0.86 (0.03)	0.71 (0.04)	0.66 (0.02)	0.76 (0.04)	0.79 (0.03)	1.00 (0.00)
	Dry Delrin®	1.10 (0.13)	0.69 (0.04)	0.84 (0.08)	0.51 (0.09)	0.70 (0.04)	0.60 (0.07)	0.84 (0.01)	0.52 (0.03)	1.00 (0.00)
	Wet HPL	0.56 (0.03)	0.59 (0.02)	0.52 (0.01)	0.21 (0.01)	0.30 (0.01)	0.20 (0.02)	0.64 (0.03)	0.57 (0.03)	0.72 (0.08)
Slippery	Dry Teflon®	0.47 (0.03)	0.30 (0.02)	0.26 (0.01)	0.27 (0.02)	0.40 (0.01)	0.33 (0.01)	0.48 (0.03)	0.40 (0.05)	0.36 (0.03)
Very slippery	Wet Delrin®	0.32 (0.01)	0.25 (0.00)	0.33 (0.02)	0.06 (0.02)	0.19 (0.01)	0.12 (0.01)	0.59 (0.05)	0.52 (0.03)	0.69 (0.04)
	Wet Teflon®	0.31 (0.01)	0.19 (0.02)	0.19 (0.02)	0.12 (0.02)	0.19 (0.03)	0.12 (0.03)	0.42 (0.02)	0.31 (0.02)	0.30 (0.01)
	Criteria met	1,2	1,2	2	2	2	2	—	—	—

*No determination could be made from the walking trials as to the relative slip resistance between dry HPL, dry Delrin®, and wet HPL as no slips were recorded on these surfaces. The ordering of these three surfaces in column #2 is one of convenience.

Column #2 shows the rank order of the surfaces from most to least slip resistance as determined by the walking trials.

Combined and connected boxes highlight homogeneous groups.

HPL, high-pressure laminate; HPS, horizontal pull slipmeter; UWT, universal walkway tester.

compliant tribometer. In particular, these three tribometers failed to differentiate between wet and dry Delrin®, which were widely divergent in creating risk of slip based on the walking trials. This finding is consistent with the observations of other investigators who have implicated drag sleds' prolonged surface residence time in creating the phenomenon of sticktion (i.e., surface-tension adhesion) (11,12,33). In the presence of sticktion, tribometers often measure a wet slippery surface as having the same or greater COF compared with a dry slip-resistant surface. Determining why the Tortus II did not appear to experience the sticktion phenomenon is beyond the scope of this research.

Three of the tribometers (English XL, Wessex, and Sigler) failed the first criteria by incorrectly ranking the wet HPL surface as being more slippery than dry Teflon®. It is possible that the effective mass of the test feet on these three devices at surface impact may be too low, thus allowing hydroplaning of the test feet in the presence of a liquid contaminant (wet HPL) compared with the dry Teflon® condition. The Mark II experienced a similar problem in meeting the first criteria in that it incorrectly ranked dry Teflon® as being more slippery than wet Delrin®.

The selection of tribometers for this study was one of convenience and availability. While we believe that the study includes the most commonly used portable tribometers in the United States, we had no usage data to support this premise. We also made no attempt to establish the reproducibility or accuracy of the tribometers. The selection of surface materials was based on our aim of developing a suite of materials that not only spanned a wide range of slip resistance during walking but could also be easily obtained and modified for use within a gait laboratory.

Direction of Future Research

The plastics (Teflon® and Delrin®) utilized in this study are not typical walkway surfaces and their material properties may diverge from those of surfaces more typically encountered. Consequently, future research should include more frequently used walkway materials if controlled manufacturing processes and continuous supply can be secured.

In order to formulate a material suite with a continuum of slip resistance (as opposed to a binary slip/no slip system), future experiments should incorporate more intermediate surfaces that, when presented to walking human subjects, may or may not cause a slip. Dry Teflon® with its ability to cause toe slips in the walking trials functioned as such a surface in the current study. Because the utilized COF at toe off is slightly higher than at heel strike during normal ambulation, we believe the toe slips recorded on dry Teflon® defined that surface as having a slip resistance in between the very slippery surfaces that caused primarily heel slips and the not slippery surfaces that caused no slips. The challenge is to identify more surfaces with and without contaminants that perform in this intermediate range in order to expand and refine a gait-based system for future tribometer validation.

This study investigated the biofidelity of tribometers under walking conditions only. As many slips and falls occur during more strenuous actions such as pushing a load or running, future research should incorporate tasks with a higher friction demand in order to evaluate a tribometer's ability to assess safety over a broader range of activities.

Conclusions

The results of our tribometer measurements were consistent with the conclusions of previous studies in that different tribometers give varied COF values for the same surface. In the current study, only two of the nine tribometers tested (the Tortus II and Mark III) met our compliance criteria by both correctly ranking all six conditions and differentiating between surfaces of differing degrees of slipperiness as established by the walking trials. These findings reinforce the need for objective criteria to ascertain which tribometers effectively evaluate floor slipperiness and a pedestrian's risk of slipping. This experimental protocol demonstrates that gait-based measures of slipperiness can be used to create reference standards against which the output of tribometers can be compared.

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