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On Threshold Values that Separate Pedestrian Walkways that Are Slip Resistant from Those that Are Not*

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ABSTRACT: Pedestrian accidents generate significant direct, morbidity and mortality costs. Slip accidents are generally a result of a number of factors. One factor that has received considerable attention is the walkway-surface slipperiness. It is desirable to be able to isolate, to the extent possible, the contribution of the walkway surface to slipperiness.

It has been the practice of those involved in evaluating walkway slip resistance to test the floor against a standard test foot under specified conditions and compare the results of that testing against a threshold. Those walkway surfaces that produce a friction coefficient above the threshold are considered acceptable.

Past and present tests and associated thresholds are discussed. Abuse issues are discussed.

It is recommended that field tests measure the available friction with a tribometer capable of correctly characterizing the friction model experienced by the pedestrian and compare that against a utilized friction threshold, determined by normative or force-plate means, for activities foreseeable in the area where a fall occurs.

KEYWORDS: forensic science, walkway safety, friction threshold, slip accidents

Magnitude of the Problem

Walkway accidents are a significant generator of medical costs and a significant drain on productivity. Buck and Coleman (1), Proctor and Coleman (2), and Proctor (3) studied walkway accidents in the workplace in the United Kingdom. The cost to that nation was thought to exceed £150 million annually (1982 data). They found a variation in accident incidence rate between industries and between employers of different size. Accident rates varied directly with age. Rice and MacKenzie (4), in a report to the United States Congress on the cost of injury, estimate that the direct (medical), morbidity, and mortality cost of fall accidents to the United States ranks with automobile accidents and firearms as a drain on the economy; fall accidents accounted for about $35 billion dollars in costs in 1986. Leamon and Murphy (5) analyzed the significance of occupational falls by an analysis of workers' compensation data from a major insurance company that covered 11% of the American privately insured work force. The authors characterize the cost of fall accidents as "enormous."

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Walkway Friction

Brungraber (6) produced an annotated bibliography of walkway safety literature. Based on studies of kinesiology and anthropometry, the author found that the coefficient of friction between foot surfaces and floor surfaces to be a significant parameter controlling slips and falls. Leamon (7) writes that floor-surface specification will continue to be required, and it will probably be wise to maintain the Underwriter's Laboratories criterion of static coefficient of friction measured, on the James machine, greater than 0.5. This should be seen to be part of the overall strategy, he writes, for there is conflicting evidence on the level of protection provided by such a measurement in normal locomotion and activities.

Research specific to pedestrian friction has been undertaken. D. James (8,9) calls into question the assumption that static friction and dynamic friction are distinct, with static always greater than dynamic. James writes that some in the field of pedestrian friction hold views that have resulted in a great deal of misunderstanding of the principles governing pedestrian stability. He writes that experimental evidence indicates that rubbers and plastics show continuous change of friction with velocity: walking is safe if friction increases rapidly as velocity increases or if, under all conditions, the coefficient of friction is greater than the utilized friction. If, however, friction decreases as velocity increases, then the situation is potentially dangerous because the requirements for stability increase as the stride is lengthened. Sometimes a decrease in temperature can change the slope of the friction-velocity relationship from positive to negative and instability in walking may result. Contaminants drastically alter the friction of all materials and mud or other wet slurries are extremely dangerous.

Lanshammar and Strandberg (10) discuss the significant mechanical differences between human locomotion and walkway-safety tribometers. For example, testing the influence of friction from the shoe's planing tendency on fluid patches requires proper scaling of forces, motions, geometrical parameters, and time. This and other relevant requirements seemed to be poorly met, they write, by most of the tribometers that they reviewed in the literature. To determine the validity of the theoretically most promising meters, their friction values have been compared with results from experiments with walking subjects. Proctor and Coleman (2) applied lubrication theory to the problem of slipping on water-wet floors and to the methods commonly used in the United Kingdom for assessing pedestrian slip-resistance. The role of the surface roughness of floors and footwear soles was evaluated, and it was shown that measurements taken by existing tribometers are open to misinterpretation. Marletta (11) studied the effects of humidity and wetness on pedestrian slip resistance evaluated with walkway-safety tribometers on selected sole and floor surface materials.

Utilized Friction

A fundamental criterion for not slipping on a walkway is that the friction needed for the pedestrian maneuver—the *utilized friction*—must not exceed the friction capability between the walkway surface and the pedestrian's shoe or foot bottom—the *available friction.* Part of the difficulty in having tribometric-test results realistically assess the slipperiness of a floor surface, especially when the floor is wet or contaminated, is that there are different mechanisms of friction—friction models—exhibited under different circumstances.

Utilized friction is determined analytically or by means of a device which measures the forces at the pedestrian's foot. The National Bureau of Standards developed an "Electronic Stepmeter" (12) in the late 1940s, what we today call a force plate, to reveal the forces involved in walking. Ekkebus and Killey (13,14) did a back-of-envelope analysis of the utilized coefficient of friction based upon the geometry of the large leg bones at heelstrike. They found results similar to force-plate analysis, i.e., that the pedestrian needs a static coefficient of friction of less than 0.4 for low-to-moderate speed, straight-ahead walking. The authors analogized the articulated strut mechanism of the James tribometer to the leg at heelstrike. With a safety factor, the authors concluded that the 0.5 value specified for the James Machine was indeed reasonable. Lanshammar and Strandberg (10) determined utilized friction by speed measurement during walking in a closed path. Grönqvist et al. (15) developed a computer-controlled tribometer consisting of a hydraulically movable artificial foot and a method for determining the dynamic slip resistance of shoes and floors by simulation of human foot motions using a force plate to record the incurred forces.

D. James (9) showed that cane and crutch tips require greater friction than shoe soles or heels; dust, which is not dangerous under normal conditions may be hazardous to those with mobility impairments. Buczek et al. (16) explored the utilized coefficient of friction of the mobility disabled during level and grade walking by having subjects walk across a force plate. The utilized friction was found to be significantly greater for the mobility disabled than for the able-bodied regardless of the speed of walking. On that basis, the regulations for the Americans with Disabilities Act (ADA) require conforming facilities use friction coefficient thresholds[2] of 0.6 on level surfaces and 0.8 on ramps.

Excessive friction too can generate injury. Menck and Jorgenson (17) studied ankle fractures during sports activities as a function of frictional forces. The frictional forces between the sports footwear and the ground can induce distortion trauma to the lower extremity. Two cases are reported in which ankle fractures are related to friction.

Available Friction

Available friction is measured by a tribometer. Tribometers for walkway safety analysis were in the United States first developed in the 1920s by Hunter (18), who developed an early articulated-strut instrument. The author examined conditions which affect the available friction of walkway materials.

The 1940s saw the development of the Sigler and James tribometers, both of which are still used today. Sigler (19) studied the relative slipperiness of walkway surfaces using a pendulum tribometer, which he developed while at the National Bureau of Standards. The surfaces were tested under wet, dry and oily, and clean and dirty conditions. Most of the floor materials showed satisfactory anti-slip properties when dry. Many, Sigler writes, would be classed as hazardous when wet. Sigler et al. (20) discuss the effects of varying some of the constants of the Sigler tribometer, such as the angle of contact between the test heel and the walkway surface, and the pressure between the heel and the walkway. They write that good anti-slip properties under wet conditions are usually associated with rough particles, which project through the film of water, and thus prevent its action as a lubricant. S. James (21) discusses the articulated-strut tribometer, which he developed, and the criterion for an acceptable floor finish: that the coefficient of friction after the application of the finish shall be at least as great, if not greater, than that of the untreated floor. The criterion is amply justified, he writes, by experience. Gavan and Vanaman (22) explored variables affecting results obtained with the James tribometer. Significantly, James tribometer tests were found to be operator sensitive, standing-time dependent, and dependent upon the rate of load application. Williamson (23) used the Bowen tribometer to determine the effect of heel size and load on the slip resistance of resilient floor coverings to determine whether there was greater variation in slip resistance among different heel materials than among different brands within each type. Other tests were designed to show the effect of moisture, floor polish, and heel materials on the slip resistance of resilient floor coverings, hard floor surfaces, and wood floor finishes.

Jung and Schenk (24) describe tests conducted by a working group of the "foot protection" ISO standardizing committee, with the participation of seven countries, using a total of ten different testing methods for determining shoe anti-slip characteristics. The test methods were compared, grouped into 16 machine variants, two selection methods, and two test-person methods. The authors found significant interrelationships between the results of the various testing machines, and concluded that no general relationship can be determined between the sole-selection methods and the tribometers.

Irvine (25) evaluated factors affecting measurements of slip-resistance between shoe-sole materials and floor surfaces. The Horizontal Pull Slipmeter tests included different floor materials, shoe sole materials, pressures, and relative humidities on both wet and dry surfaces. The results proved to be sensitive to relative humidity, sole pressure, replication, and wet/dry conditions. The author concluded that it is possible to identify shoe-sole materials that have desirable slip-resistant qualities for various floor surfaces under wet and dry conditions.

Brungraber (26) describes the design and development of the Slip Test portable articulated strut tribometer (PAST), loosely based upon the James tribometer. (It should not be inferred that PAST results necessarily match James tribometer readings.) Braun and Brungraber (27) describe a series of comparative tests made with the Slip Test PAST and an experimental laboratory drag sled; both the testers yielded significantly similar results.

Adler and Pierman (28) summarize the United States National Bureau of Standards walkway and shoe slip-resistance measurement research from the 1920s through the 1970s, i.e., the work

[2]Thresholding refers to the mathematical operation of mapping an ordinal or numeric variable into a qualitative (categorical) one. (For the purposes of this paper, the qualitative variable is dichotomous; that restriction is trivially relaxed.) A simple, everyday example of this concerns vehicle speed. If the speed limit on a given road segment is 50 mph, a driver traveling ≤50 mph is not speeding. A driver traveling at >50 mph is. Thus, the thresholding operation maps the vehicle speed—a continuous variable—into the qualitative set {not speeding, speeding}. *Threshold* in this paper refers to the numeric value that lies at the border between the two categories. In this hypothetical example, the threshold value is 50 mph. In the body of the paper, the qualitative, dichotomous set is typically {slip resistant, not slip resistant}.

of Hunter, Sigler, Boone, and Brungraber, and outline activities designed to underpin a technical basis for slip-resistance measurement.

D. James (29) compared Tortus and PRL skid tests. The corresponding safety criteria usually associated with these tests are assumed to be equivalent, James writes when, in fact, experimental results show that the opposite is true, even when the same test-foot material is used on each tribometer. Andres and Chaffin (30) describe a number of tribometers and techniques which attempt to quantify the static or dynamic coefficient of friction of shoe and floor-surface interfaces. Bigfoot, Slipometer, Slip Test PAST, British Portable Skid Tester, Tortus, and FIDO were tested in laboratory and field studies. Device consistency, repeatability, accuracy, and ease of use were examined for a variety of shoe, floor, and floor preparation conditions. Bailey (31) compared the Tortus and the Pendulum dynamic tribometers.

Kulakowski et al. (16) evaluated the performance of three slip resistance testers: the Slip Test PAST, the Horizontal Pull Slipmeter, and the Pennsylvania Transportation Institute Drag Sled Tester. Each tester was used to measure the slip resistance of selected surfaces representing a wide range of frictional characteristics of typical indoor and outdoor surfaces. The testers were evaluated with respect to their applicability, precision, repeatability, and sensitivity to the operator's measuring technique. The correlation was determined between the results produced by the testers on the same surfaces. A series of experiments were conducted with human subjects walking over surfaces having relatively low slip resistance. The objective was to determine whether people will slip more often on surfaces that are measured as having lower slip resistance. In general, the agreement between the results of slip resistance measurements and the results of the biomechanical tests was high. Redfern et al. (32) developed a computer-controlled dynamic coefficient of friction tribometer for use in determining shoe/floor slip resistance. They found that the tribometric measurements were highly repeatable. Brungraber et al. (33) describe the ASTM/Bucknell University F-13 Workshop to evaluate different tribometers. The tribometers in general produced different results, and, for wet testing, produced remarkably different results. Marpet (34) described the results of that workshop.

Chaffin et al. (35) compared a variety of static and dynamic walkway-safety tribometers. The authors review the basic physics of such tests and describe a set of experiments to determine the static and dynamic coefficient of friction values under operating conditions known to exist in different situations. They define a set of conditions wherein hazardous friction situations potentially exist. The authors question the use of light-load testing devices and the use of static and slow-speed reference friction values in current use.

Criteria for Slip-Resistant Walkways

There have existed and now exist a number of criteria for separating slip-resistant and not-slip-resistant floors:

- that any treatment shall not lower the friction of the untreated floor;
- that the slip distance of the heel along the floor shall be limited; and,
- that the friction coefficient must exceed a threshold value.

James (21) describes the criterion that a polish shall not lower the available friction.

Perkins (36) and Perkins and Wilson (37) measured slip between the shoe and ground during walking. The authors write that practical slip experiments, using a number of male subjects walking in rubber-soled shoes on an oily steel surface, have shown that the severity of a slip can be measured by the distance through which the shoe slips. Slip distance was found, by experiment, to be inversely related to the static-friction coefficient. The occurrence of slip was linked to specific peaks on the friction plot. Using stroboscope photography, they showed that most dangerous slips on an oily steel surface start when the shoe is stationary. Perkins concluded that the static friction coefficient is the most relevant for slip-resistance testing, but it is essential to reproduce the short time of contact of the shoe with the surface. Perkins and Wilson found that slip severity depends on how friction changes as the shoe moves. Furthermore, they write that a single measurement of friction may not be sufficient to completely predict the slip resistance of a shoe bottom.

Leamon and Son (38) found that, during locomotion, small, frequently undetected slips take place at heelstrike. Under certain circumstances, these microslips develop into uncontrolled sliding which in turn leads to a fall. The authors report on the relationship between foot attitude, slip patterns, and the forces involved in the "slip/stop cycle" for different walking speeds and levels of floor slipperiness. Leamon and Li (39) investigated slip length at heelstrike and the pedestrian's perception of slipping. The authors found that slip distances of less than 30 mm may not be reliably discriminated by subjects; above this distance, subjects can reliably identify the fact that they have slipped. It appears that any combination of walking speed and dynamic coefficient of friction which will produce slipping distance in excess of 30 mm will be perceived as a slippery condition. The qualitative description of events occurring at the heel may be classified as microslip (0 to 30 mm), a slip (30 to 100 mm) and a slide (>100 mm).

Leamon (40) writes that coefficients of friction of floor surfaces have not been shown to be good predictors of slipping. Human subjects appear to be able to perceive slipperiness and modify their gait to mitigate the effects of slippery surfaces. The author investigated the subjective ranking of floor surfaces, the slip distances actually generated with experimental footwear on test surfaces, and the measured coefficients of friction. Foot-slip distances for these experimental conditions appeared to be nonsignificantly different, although the coefficients of friction were significantly different. The length of the slip, which appears to be related to the probability of the fall, seems to have an exponential relationship with the dynamic-friction coefficient. Leamon and Li (41) exposed subjects to a slippery surface while carrying a load. The addition of the load significantly increased the average slip distance at both slow and high speeds. This suggests that it is not sufficient to identify the maximum frictional demand, but account should be taken of the friction at parts of the gait cycle besides heelstrike. Myung, et al. (42) studied heel-slip distance in an experiment conducted to investigate simultaneously both tribological and biomechanical factors of slipping. Subjects were asked to walk on different floor surfaces at a fixed cadence. Slip distance was found to exponentially decrease as the static coefficient of friction increased. Slip distance increased logarithmically as stride length increased.

Manning, et al. (43) studied a method of ranking the grip of industrial footwear on water wet, oily, and icy surfaces by lubricating the walking surface with a water-based wetting agent and four grades of mineral oil, and on wet and dry ice. The maximum friction coefficient attained before each slip was recorded while walking forwards and while walking backwards on the heels. Results for the 13 footwear samples were ranked in order of friction coefficient. For each floor and lubricant combination, the authors found that friction coefficient recorded while walking backwards was about 40% lower than the forward walking friction coefficient, supporting the hypothesis that dangerous slips are likely to occur on heel strike. There was also a significant correlation between shoe-sole roughness and friction.

Sacher (44,45) discusses the history of use of the 0.5 static coefficient, and the relationship of the 0.5 static coefficient of friction—the threshold between surfaces that are nonslip and surfaces that are not—and the James tribometer. Sacher notes that the James tribometer was developed and used before the 0.5 threshold value came into use. In 1945, James submitted a recommendation to Underwriter's Laboratories Casualty Council that 0.5 be considered the minimum acceptable friction coefficient: "Materials which have been found by experience to provide adequate underfoot safety have shown coefficients of at least 0.50." In 1951, the Federal Trade Commission proposed rules that prevented polish and wax manufacturers from using the terms *non slip, slip proof,* or words of similar import, unless those polishes exceeded a coefficient of friction of 0.4 using a Sigler pendulum tribometer or, alternatively, 0.5 using a James tribometer. The ASTM Committee D-21 on Floor Wax and Polish was formed in 1950. In 1964 ASTM Committee D-21 issued tentative standard D 2047-64T for "Static Coefficient of Friction of Waxed Floor Surfaces," which became an official standard in 1970. That standard, ASTM D 2047-69, Sacher writes, referenced the James tribometer and was adopted by the Chemical Specialties Manufacturers Association in conjunction with the 0.5 threshold value. ASTM Test Method D 2047 adopted the 0.5 value in 1975.

Fendley, et al. (46) suggest the use of ratiometric analysis, dimensionless numbers, and subjective scoring for the development of a comprehensive slip-prediction model. They write that heel slip, responsible for most slip-induced falls, is attributable to a number of disparate, interrelated elements. This paper uses ratiometric analysis, dimensionless numbers, and subjective scoring to determine the structure of a model for heel-slip prediction. They wrote that much needs to be accomplished before such a comprehensive slip-prediction model becomes an operational reality.

Discussion

There is a considerable amount of misunderstanding and a certain amount of intellectual misconduct surrounding the meaning and use of friction thresholds. This is perhaps because thresholds can represent two distinctly different, but related, items: first, the 0.5 (or 0.6) value is commonly used as a utilized coefficient of friction value that represents a safe value for walking under many, but not all, foreseeable conditions. Secondly, 0.5 represents an acceptance-test value in the ASTM Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine (ASTM D 2047), and 0.6 represents the acceptance threshold for level-surface ADA compliance. The former 0.5 (or 0.6) value is a utilized-friction coefficient value, determined by means of pedestrian walkway research using kinetics or kinematics techniques. The latter 0.5 (or 0.6) value is an available-friction threshold, determined by using, for the 0.5 value, a James tribometer, and for 0.6, an ADA-approved tribometer.

The utilized-friction coefficient is the ratio of tangential to normal force at the floor needed—utilized—between the pedestrian and the walkway surface to allow the pedestrian to perform a desired action without slipping. It is a function of the pedestrian's gait and actions, and can be estimated by an analysis of gait geometry or measured by having the pedestrian walk or perform some other desired action on an in-ground force plate. It is important to note that the utilized friction is not directly a function of the shoe bottoms, the walkway, or the presence or absence of water or contamination between the shoe bottom and the walkway. Because pedestrians adapt their gait to the conditions at the walkway, changing the utilized friction, walkway conditions indirectly, filtered through changes in gait, do effect the utilized friction.

Ekkebus and Killey (14) determined the utilized coefficient of friction by trigonometric analysis of the simplified geometry of the leg bones at heelstrike. Their analysis and force-plate measurements show that straight-ahead, level-surface walking at moderate speed produces a friction requirement of about 0.35 to 0.4. To get from a determination of utilized friction to testing available friction with a tribometer, Ekkebus and Killey analogized the leading leg at heelstrike to the articulated strut of the James tribometer at breakaway. Their analysis linking the James tribometer and the utilized friction is in fact common to all strut-based tribometers, and not just the James.

The 0.35 to 0.4 friction requirement is unrealistically low. Changing direction requires lateral force, which increases the friction requirement. Gait anomalies may increase the peak surface-plane forces, also increasing the friction requirement. Over 20 years ago, Ekkebus and Killey made the observation that 0.5 seemed to give enough of a safety factor, so that normal walking at normal speed by not-handicapped pedestrians will generate a negligible probability of slipping.

The 0.5 friction requirement does not cover all pedestrians; it does not cover all situations. James (9) and Buczek, et al. (16) discussed the friction requirements of the mobility impaired. James put forth a geometric analysis of the friction requirements of a crutch-using pedestrian. Buczek, et al., used a force plate to measure the friction requirements of mobility-impaired pedestrians. Both studies found that those with mobility handicaps required higher levels of friction to safely traverse an area. Implicit in the 0.5 friction requirement for ordinary pedestrians is a limitation on the step length. Ekkebus and Killey wrote that, for a person to exceed the 0.5 friction requirement, that person would need a 37-in. (94-cm) hip-joint-to-floor measurement and a 33-in. (84-cm) stride. The authors write that "it is not impossible for a person of 27-in. (69-cm) hip joint to floor measurement to take a 33-in. (84-cm) pace, it is extremely awkward and very unlikely indoors. Outdoors on a military parade square, this pace might be obtained *but never indoors* (*italics* mines). In fact, for a number of reasons, this is not always correct. First, Ekkebus and Killey's pedestrian sample ($n = 16$) is too small to ensure robust inference. Second, and significantly, there exist pedestrian spaces where one can *expect* hurried walking. An obvious example: a hospital corridor where medical personnel must sometimes respond to a STAT call.

In pedestrian accident reconstruction, it is often necessary to estimate the utilized friction coefficient of either a hypothetical prudent pedestrian or of an injured party. As a rule of thumb, in situations in which unhurried walking is the foreseeable 'normal' activity, it is reasonable to use 0.5 as the utilized coefficient of friction. A higher value would be used, e.g., for a pedestrian using crutches or similar mobility aids; a lower value would be used where the physical environment prevents taking a normal-size step, e.g., a cramped bathroom or closet.

The 0.5 threshold value specified in ASTM Test Method D 2047, although it has its roots in the friction required for a pedestrian to traverse safely an area, is, in fact, separate from that. ASTM D 2047 contains an acceptance criterion for a floor polish tested under rigidly specified conditions. A floor polish that meets or exceeds the 0.5 threshold can be labeled *Slip Resistant.* To ensure consistency, the test surface to which the polish is applied, the method of polish application, the test foot, test-foot preparation, the test design, and criterion for intra- and inter-laboratory precision (repeatability and reproducibility, respectively) are specified.

It is important to understand what it means to use a floor polish that is slip-resistant:

• It means that the polish has passed an acceptance test that has been in use for decades. It means that, in general, a prudently walking pedestrian probably won't slip. Sacher (43) writes that ASTM Test Method D 2047's 0.5 threshold has factored into it the

> . . . slipping experience (over a period of years) of large numbers of people walking on floors of every type . . . [floors] which were not always new, freshly prepared, scrupulously dry or clean, or even level . . . Nevertheless, it was tacitly understood that the "field" correlation with the standard, *per se,* is most meaningful when applied and limited to "normal," unencumbered walking at the generally accepted pace of three miles per hour . . . at regularly, well maintained, level surfaces, free of gross debris or contamination of any type. . . .

• It does not mean that the walkway surface to which the polish is applied will or will not be slip resistant. There are two reasons for this. First, because ASTM D 2047 is a laboratory-only test; testing a floor *in situ* requires field testing. Applying ASTM Test Method D 2047 words *Slip Resistant* to a floor—rather than a polish coated on a specified test surface in a specified manner—requires the assumption that laboratory-only James-tribometer testing is an acceptable surrogate for field testing. Secondly, even if Slip-Resistant floor—*Slip Resistant* again in the ASTM Test Method D 2047 for sense—*were* capable of definition, the fact that the floor polish passed the ASTM Test Method D 2047 for slip-resistance does not imply that the polish applied to a given floor would create a floor that is reasonably safe. A Slip-Resistant polish may be misapplied, it may be an inappropriate polish for the surface upon which it is applied, or it may be that the pedestrian friction requirements exceed 0.5 because, for example, sports are played on the surface, pedestrians must walk hurriedly, for handicapped-access needs, or because the surface is not level.

• It does not mean that a person cannot slip on a floor coated with the Slip-Resistant polish. This follows from the fact that a floor coated with a Slip-Resistant polish may not be slip resistant.

• It does not mean that a party controlling a floor will be immune from liability if a person should slip and sustain injury. This follows from the fact that—standards or no standards—a premises must be reasonably safe for its intended purpose.

Complying with ASTM Test Method D 2047 gives the manufacturer of the floor polish a limited defense: a polish which passes a properly conducted ASTM Test Method D 2047 test *clearly* meets the standard of the floor polish industry with respect to slip resistance. The defense is limited in that applications where the polish would not be expected to provide slip resistance must be clearly delineated by the manufacturer. That means appropriate *Warnings* or *Cautions* are necessary. A few examples where a Slip-Resistant polish probably will not result in a Slip-Resistant floor: on ramps, because the utilized friction is higher on a ramp than on a level surface; in hospital corridors because, as noted above, it is foreseeable that medical personnel will be rushing around in an emergency; in a place where it is foreseeable that the surface will become wet (exit vestibules or bathrooms); and in areas where grease and oils will foreseeably find their way to the floor (kitchens or workshops).

The user of a Slip-Resistant polish is given far less protection by using a polish which meets ASTM Test Method D 2047 than is the polish manufacturer by manufacturing a polish conforming to ASTM Test Method D 2047. The user must show that the polish is slip resistant in the specific application where the polish is used. This may be obvious in a situation where the polish is applied to a walkway which roughly meets the ASTM Test Method D 2047 test conditions: a level area, kept clean and dry, where pedestrians do not hurry as they walk in a generally straight-ahead direction. Using a Slip-Resistant polish in an area which gets wet will afford the polish user no protection whatsoever: The James tribometer is not to be used for wet-surface testing. Sacher (43) calls wet testing ". . . almost purposeless, meaningless, and non-reproducible . . . and for which there are no generally accepted definitions or standards." Sacher goes on, "We already know that wet surfaces are dangerous for some and hazardous for all."[3]

Ideally, a walkway surface should be specified to be reasonably slip resistant before it is installed by estimating the utilized friction needed for the area's reasonably foreseeable activities, and then ensuring, by testing with a tribometer that mimics the friction model at the pedestrian's feet, that the floor has available at least that amount of friction. Thus, the selection of a floor surface must be dictated by more than just aesthetics; any selected floor surface should, in conjunction with its specified maintenance routine, be inherently slip resistant. Importantly, surfaces that will foreseeably get wet, contaminated, muddy, or oily should have a surface and maintenance regime selected that will be slip resistant under those conditions.

Use and Abuse of the 0.5 (and the 0.6) Friction Coefficient Value

None of what is written above should be taken as criticism of the ASTM Test Method D 2047 standard. ASTM Test Method D 2047 and the James tribometer are certainly satisfactory for the limited, but important, purpose of qualifying the dry-surface slip resistance of a floor polish applied to a smooth-floor surrogate as *slip resistant* or *not slip-resistant.* Decades of use in that application show it to be satisfactory. ASTM Test Method D 2047 is an ASTM *voluntary consensus* standard, and not merely an industry standard. Like all voluntary consensus standards, the standard-development process ensures that all points of view, and not just the point of view of the floor-polish manufacturer, are fairly considered.

The problem with ASTM Test Method D 2047 stems from the way some misuse it and its 0.5 friction threshold. First, there are some who attempt to use ASTM Test Method D 2047 and the James tribometer for uses far beyond the standard's scope and the instrument's envelope. And secondly, there are those who argue that,

[3]It is probably fair to say that most walkway surfaces that ASTM Committee D-21 has interest in—smooth floors to which polish could be applied—may well be slippery when wet whether or not a polish is used. Broom-finished concrete and certain sand-finished ceramic tiles and indoor-outdoor carpets are aggressively non-slip when wet. These are not floor surfaces upon which polish would be applied; they are therefore out of the purview of Committee D-21.

because the 0.5 static friction coefficient value serves as the threshold value for ASTM Test Method D 2047, no other test methodology can use that 0.5 value as a floor-safety criterion.

A standard can carry significant weight in litigation. The absence of a meaningful, on-point standard does not per se mean that tests are meaningless. (Would the James tribometer test for polish-coated floors be meaningless if the ASTM Test Method D 2047 standard had never been written?) Of course, any test conducted without the benefit of a voluntary consensus (or other legitimate) standard underpinning it must rise or fall on its own merits. Many investigators wish to wrap their experimental results in the mantle of a standard. ASTM Test Method D 2047 is subject to significant abuse, perhaps because it has been around for a long time, and certainly because it carries an acceptance threshold. The ASTM Test Method D 2047 standard for polish-coated floors should only be used within its scope. That is, if one chooses to assert that the ASTM Test Method D 2047 standard is met, one must meet each and every facet of that carefully developed document. At the risk of writing what is plain, the 0.5 acceptance threshold contained in ASTM Test Method D 2047 should only be applied to the qualification of liquid floor polishes tested with the James tribometer and the protocols listed in the standard. To sum this up, if a test does not comply with all aspects of ASTM Test Method D 2047, ASTM Test Method D 2047 should not be referenced.

Hence, the following implicit or explicit references to ASTM D 2047, (all of which I have come across in forensic reports) constitute examples of clear misuse of the ASTM Test Method D 2047 standard:

- "ASTM Test Method D 2047 tests" using tribometers other than the James;
- Tests "using the equipment described in ASTM Test Method D 2047," that is, the James tribometer, for wet testing;
- "exceeding the recognized minimum coefficient of friction of 0.5 for slip-resistant walking surfaces under both dry and wet conditions" for horizontal-pull dynamometer (ASTM C 1028) tests;
- "tests run according to the ASTM Test Method [D 2047] method with wet- and dry-sensor interface conditions."

In short, *almost* conforming to ASTM Test Method D 2047 is like being 'a little pregnant': an oxymoron.

There is another side to friction-threshold abuse: I have seen the argument that no tribometer results other than those generated by the James tribometer are meaningfully applied to the question of pedestrian safety because only ASTM Test Method D 2047 and the James tribometer have associated with them the 0.5 threshold value. Similarly, it is argued that the 0.5 threshold can only be used in conjunction with the ASTM Test Method D 2047 standard. 0.5 is, in effect, 'owned' by ASTM Test Method D 2047. These arguments are as silly as the incorrect quotations in the paragraph above this one are cynical. It is just as incorrect to attempt to place non ASTM Test Method D 2047 tests under the mantle of ASTM D 2047 as it is to assert that the ASTM Test Method D 2047 standard is the last word in pedestrian safety. To seriously assert that a 0.5 James machine threshold is *the* test—rather than a test—for protection against pedestrian slipping is to confound the measuring stick with the measurement. Just as important: if ASTM D 2047 were the only way to assess the slip propensity of walkways, than only polish-coated floors could be assessed!

Although analogous problems do not yet exist for the ADA-mandated friction thresholds of 0.6 and 0.8 for level surfaces and ramps, respectively, the ADA requirements carry their own negative baggage. The development of the ADA requirements relied upon research that is arguably flawed. It is not clear just how the guidelines are to be applied. The acceptance test situation is muddled, in part because of the initial research flaws, and in part because of later rule-making decisions.

The original work on the friction requirements for the mobility impaired by Buczek, et al. (16), used a force plate to record the friction requirements of the subjects. Utilized friction should be, as a first-order approximation, a function of gait only, independent of footwear and test surface. Available friction thresholds were developed using a Slip Test PAST tribometer and, for the most part, using a Silastic 382 test foot. This test-foot material is used as a skin surrogate (a foot bottom rather than a shoe bottom) and used for tribometer calibration. To the extent that the 0.6 and 0.8 thresholds were developed using the force-plate data, they should be defensible. To the extent that the thresholds were set using the data from a Silastic-382-shod tribometer, they are flawed.

There is a serious question of to whom and to what the ADA thresholds apply. Friction coefficients apply to facilities. That implies that, on a handicapped-accessible route, the 0.6 and 0.8 thresholds apply; in areas not handicapped accessible, these standards do not. If an able-bodied pedestrian slips on a level walkway on a handicapped-accessible route, and the friction coefficient is measured to be, say 0.55, above the utilized friction needed for ordinary walking but below the ADA threshold, the facility is not ADA compliant with respect to slip resistance. But is it liable for a slip that occurred at a friction level above which the able-bodied person should have been safe? In other words, *should* the ADA requirements apply to a nonhandicapped person?[4] Another unresolved question: where would the responsibility lie if a mobility-impaired pedestrian fell in a public space that was not part of an handicapped-accessible route? For example, where would the liability rest if a hotel had handicapped-accessible rooms but, for whatever reason, a handicapped person was rented and sustained a fall in a nonhandicapped-access room?

There is an absence of clear guidelines as to how to test for conformance to the ADA requirements. A number of tribometers appear to be ADA-acceptable for available friction verification, including the Slip Test PAST. The original research used, as I noted above—either exclusively or for the most part—a Silastic 382 skin-surrogate test foot. It is not clear whether the same test foot should be used in ADA acceptance testing. Sacher (44) writes that,

> the Slip Resistant Surfaces Advisory Guidelines (0.6 level, 0.8 ramp [using the Silastic 382 test-foot material]) are misleading at first sight and are spuriously high. In fact, these values, when translated to leather, would probably be lower than the venerable 0.5 static coefficient of friction requirement of ASTM D 2047 for a nonhazardous walkway surface.

It is not clear whether or not the 0.6 and 0.8 requirements are in fact incorrect. What is clear is that the lack of clarity on this issue will spawn unnecessary complications and litigation.

Finally, the very fact that there exist multiple thresholds, multiple tribometers, and multiple test-foot materials gives opportunity for

[4]The only thing clear is that, if the person who falls becomes handicapped as a result of that fall, that unfortunate pedestrian would then certainly be covered by the ADA requirements. Thus, if that unfortunate pedestrian again fell at that same location, the ADA threshold would definitely apply and, the second time around, the facility would clearly be responsible for the slip.

unscrupulous to act by picking and choosing from that smorgasbord which will support a predetermined set of conclusions. Legitimacy mandates that thresholds must be selected on the basis of either strict conformance to ASTM Test Method D 2047, for acceptance testing a floor polish, or on the basis of reasonably assessing the utilized friction in an area. And tribometers must be selected on their match to the appropriate friction model.

Conclusion and Recommendations

As I wrote above, Leamon (7) writes that floor-surface specification will continue to be required and it will probably be wise to maintain the Underwriter's Laboratories criterion of static coefficient of friction measured, on the James machine, greater than 0.5. This should be seen to be part of the overall strategy, for there is conflicting evidence on the level of protection provided by such a measurement in normal locomotion and activities. According to Leamon, the James-tribometer test's

> ... main advantage might be as a legal defense, rather than as a particularly useful tool in producing safer work places. It is sobering for practitioners, who are seeking to improve their performance with regards to slipping and falling accidents, to find that the 1989 publication of the Chemical Specialties Manufacturers, Inc. on "Waxes, Polishes, and Floor Finishes Test Methods" recognizes, in a statement quoted by Steinle (1961) "It is now generally accepted by those engaged in this study that machine measurements of the coefficient of friction cannot correlate in all cases with foot tests on the floor or with safety in use." [Furthermore,] ... there are presently no standards of floor safety that can be expressed in terms of accident frequency, coefficient of friction, or subjective foot tests in the field.

In hindsight, had Ekkebus and Killey any idea of how often quoted—and misquoted—their papers would be, they probably would have spent a lot more time refining them. And again, in hindsight, had S. James had any idea how far the 0.5 threshold value would go when he proposed it, he might well have spent more time rigorously justifying it. This brings to the fore a perceived but significant weakness in the ASTM Test Method D 2047 standard—that little analysis besides Ekkebus and Killey's after-the-conclusion-was-reached work underpins the 0.5 acceptance threshold. In spite of the well-known shortcomings of the James Tribometer (22), decades of experience suggest that ASTM Test Method D 2047 is reasonable for assessing the safety of a floor polish under ordinary conditions. But experience is not the same thing as 'proof.' I disagree with Sacher's use of the word "derived" in his observation that the 0.5 static coefficient of friction threshold which eventually found itself in ASTM Test Method D 2047 was "*derived* from the correlation of laboratory test results with the actual 'slipping' experience (over a period of years) of large numbers of people walking on floors of every type." In fact, that value which "experience (over a period of years) of large numbers of people walking on floors of every type" appears to have *a posteriori* justified, was *derived* long before the ASTM Test Method D 2047 standard in a manner which probably rested, *a priori*, squarely on James' intuition. I am not at all suggesting that that threshold was or is incorrectly set. (Below, I suggest its use under certain conditions.) Rather, when the threshold was first considered, generations ago, there seemed to be more faith in scientific and engineering intuition than exists today. Today, statistically rigorous proof is needed even for that which seems correct; here, statistically rigorous proof is lacking.

The question of where to set the friction threshold used to separate slip-resistant surfaces from not-slip-resistant surfaces is ultimately a societal question: Who is to bear the burden of paying the costs of safe walkways and fall injuries? Any threshold value that is picked shifts that burden. Raising the slip-resistance threshold moves the burden away from those who would be injured and towards facility owners and operators; lowering the threshold puts the burden on and shifts the costs to those who sustain injury. (Setting a walkway friction threshold in that context is clearly beyond the scope of this paper.)

There is, however, an obvious safety criterion which can be used if slips are to be prevented; that the available friction must exceed the utilized friction, i.e., $\mu_{available} \geq \mu_{utilized}$. The utilized coefficient of friction is mostly a function of pedestrian gait and has nothing at all to do with the ASTM Test Method D 2047 or any other test standard:

- Under circumstances where pedestrians *clearly know* that a walkway is slippery, they can adjust their gait so that they require less friction than the 0.3 to 0.4 range, usually considered the minimum needed for safe traverse.
- For level-surface, average-walking-speed conditions, the utilized friction, based on gait analysis and force-plate studies, and given a safety factor, can be considered to be 0.5.
- For the mobility impaired or where hurried ambulation is a necessity or clearly common, the utilized friction (again based upon gait-geometry and force-plate studies) can be considered to be 0.6.
- For running and sports, and for walking on ramps, the utilized friction will often need to exceed 0.6.

In sum, any standard-independent friction threshold is a function of the pedestrian's activity. For ordinary walking, the list above indicates that the available friction must meet or exceed 0.5 utilized friction: $\mu_{available} \geq 0.5$.

This criterion looks the same as the ASTM Test Method D 2047 acceptance threshold because both are underpinned at some level by the requirements of ordinary pedestrian gait. Thus, the 0.5 value is, under appropriate conditions, a reasonable threshold on other-than-polish-coated floors. Conversely, the 0.5 threshold value may, in certain circumstances, be inappropriate for field tests on a polish-coated floor. For example a polish-coated surface on a ramp would require a higher friction coefficient than 0.5.

Although the available friction is measured by a tribometer, the general criterion does not specify either a tribometer or a testing. It is well known that different types of tribometers give different results; the major reason for this seemingly anomalous situation is, again, that different tribometers measure different types of friction—different friction models. Matching the friction model underpinning the tribometer to the situation under test provides a basis for determining which tribometers are appropriate (and which are inappropriate) for a given field situation.

In wet-surface falls, for example, the friction model is hydrodynamic. In a wet-surface slip, the foot at heelstrike fails to be decelerated because the heel planes over the walkway surface on a film of water or other liquid. For tribological tests to be meaningful, the tester must be able to reproduce the hydrodynamic situation that confronts the pedestrian. Minimally, that means that the time between the application of the normal and tangential forces must be effectively zero. Two tribometers that accomplish this by design are the Slip Test PIAST and the English variably inclined strut tribometers. In these two devices, the test foot descends to the test surface at an angle, the tangent of which the friction coefficient. The pendulum-type dynamic tribometers (the Sigler and the British Portable Skid Tester (BPST) arguably apply the forces in a manner that should allow realistic wet testing.

Contrast this with articulated strut or drag-sled testers in which the load (the normal force) is applied before the in-plane force. In the Slip Test PAST, the time between the application of the load and the lateral force can be as little as a fraction of a second. For the James tribometer and for drag-sled devices, the time can range from a few seconds to a minute or more. In either case, the time between the application of load and the time the test foot moves, stopping the test, is greater than the time it takes for the test foot to travel through the film of water and contact the test surface, changing the friction model from hydrodynamic—planing on the water film—to contact.[5] Thus, articulated-strut and drag-sled tribometers should not be used to determine the wet-surface friction that a walking pedestrian will encounter. On a water-wet surface, a variably inclined strut or a pendulum tribometer should be used. In short, it is important to match the tribometer to the friction model experienced by the pedestrian.

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[5]Imagine trying to determine the *friction* of a skiing water-skier by dividing the weight of the ski-shod skier by the tension in the rope. The skier should be planing on the water when this test is accomplished. It would not do to have the water skier jump into the water and then measure the tension in the rope as the skier is pulled *through* the water. Articulated-strut and drag-sled tribometers used in wet-surface tests accomplish exactly that.

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