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Required Coefficient of Friction Versus Top-Piece/Outsole Hardness and Walking Speed: Significance of Correlations*

REFERENCE: Fendley AE, Medoff HP. Required coefficient of friction versus top-piece/outsole hardness and walking speed: significance of correlations. J Forensic Sci 1996;41(5):763–769.

ABSTRACT: Slip resistance of shoes in relation to walkway surfaces is of importance to forensic science. Pedestrians adapt to changes in shoe construction, walkway, and interface characteristics by altering patterns of movement. The instantaneous ratio of tangential to normal ground reaction forces (required coefficient of friction) is affected by such movement alterations. Slip probability depends on the ratio of required to available coefficient of friction (μ_r/μ_a). However, there are practical problems in application of this concept. Adequate assessments of the safety of footwear/walkway-surface interactions should take into account subject tests of μ_r in actual walking scenarios as well as material tests of μ_a and relevant footwear/walkway characteristics.

Based on the literature, this paper discusses the relationship of μ_r to top-piece/outsole hardness and walking speed. A pilot experiment is described in which subjects walked across a force plate at a series of increasing speeds wearing shoes with the top-piece/outsoles replaced by various test materials. Correlations of μ_r versus top-piece/outsole hardness and walking speed are presented from data analysis of a single representative subject. The paper explores how biomechanical adaptations of the subject to his footwear may account for the fair-moderate correlations observed.

KEYWORDS: forensic science, engineering, top-piece, outsole, required coefficient of friction, available coefficient of friction, tribometer, slips, fall accidents

Required coefficient of friction (μ_r), as it relates to both footwear-outsole/walkway-surface characteristics and walking velocity, impacts on pedestrian safety. Adequate assessment of the slip resistance of footwear in interaction with walkway surfaces is a matter of concern in forensic science. Traction/safety determinations must be based not only on material tests, but also on subject tests involving actual walking scenarios (gait/footwear/walkway-surface combinations). To date, μ_r has not been systematically studied in relationship to top-piece/outsole hardness or walking speed. Footwear and walkway surface properties, such as hardness, will affect μ_r. These properties can alter human proprioception (1,2), which provides the sensory basis for an individual to alter his or her gait. Changes in movement patterns (3), and in the magnitude and point of application of ground reaction forces (4), result from footwear/walkway-surface interactions, and may in turn influence μ_r.

Experimentally, the ratio of μ_r/μ_a, where μ_a is the available coefficient of friction measured by a specific tribometer, can be related to the probability of slipping during gait (5,6). Historically, it has been assumed that a person will not slip if μ_r is less than μ_a. There are several problems associated with the application of this concept. Among them are inconsistencies in the design and operation of tribometers for measuring μ_a, inconsistencies between measurement techniques for μ_a and μ_r, and the varying effect of different materials and contaminants on operant friction mechanisms.

As defined here, static μ_a is the ratio of tangential force/normal force determined by a tribometer at the point of impending slip between the tribometer sensor and a surface. Dynamic μ_a is the ratio of tangential force/normal force determined by a tribometer while there is slipping between the sensor and the surface. μ_r, determined from a force plate experiment, is the peak observed tangential force/normal force ratio calculated for an individual human subject engaged in given walking scenarios. These scenarios do not involve slipping, nor do they necessarily involve an impending slip.

Since slip probability depends not only on μ_a, but in part on μ_r/μ_a, its adequate evaluation in the field requires further study of the alteration of μ_r by footwear-material hardness and by walking speed, among other factors. Clearly, both μ_r and μ_a must be taken into account in the development of slip-resistance standards for walkways and shoes. Historically, the ASTM Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine (ASTM D 2047-93) states that 0.5 is the minimum static μ_a, measured by the James machine, for a slip-resistant walkway surface. A μ_a of 0.5 has been deemed safe, on the basis of a geometrical walking model, for persons walking indoors (7), but has been questioned for fast-walking subjects (8) and for mobility-impaired persons (5,6,9). Slip-safety ranges for top-piece hardness recommended by SATRA have been based on studies of μ_a for various top-pieces measured by the SATRA slip tester (10).

This paper presents data analysis for a single representative subject from a force plate study of μ_r versus hardness of top-piece/outsole materials and walking speed. It explores the importance of this type of study based on previous investigations from the literature of slip probability in relation to coefficients of friction.

Methods and Materials

The experiment took place at the Pennsylvania State University Center for Locomotion Studies in July 1993. It was performed by members of the ASTM Committee F-13 on Safety and Traction

Received for publication 15 Sept. 1995; revised manuscript received 6 Oct. 1995; accepted for publication 10 Oct. 1995.

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*Presented in part at the 47th Annual Meeting of the American Academy of Forensic Sciences, Seattle, WA, February 1995.

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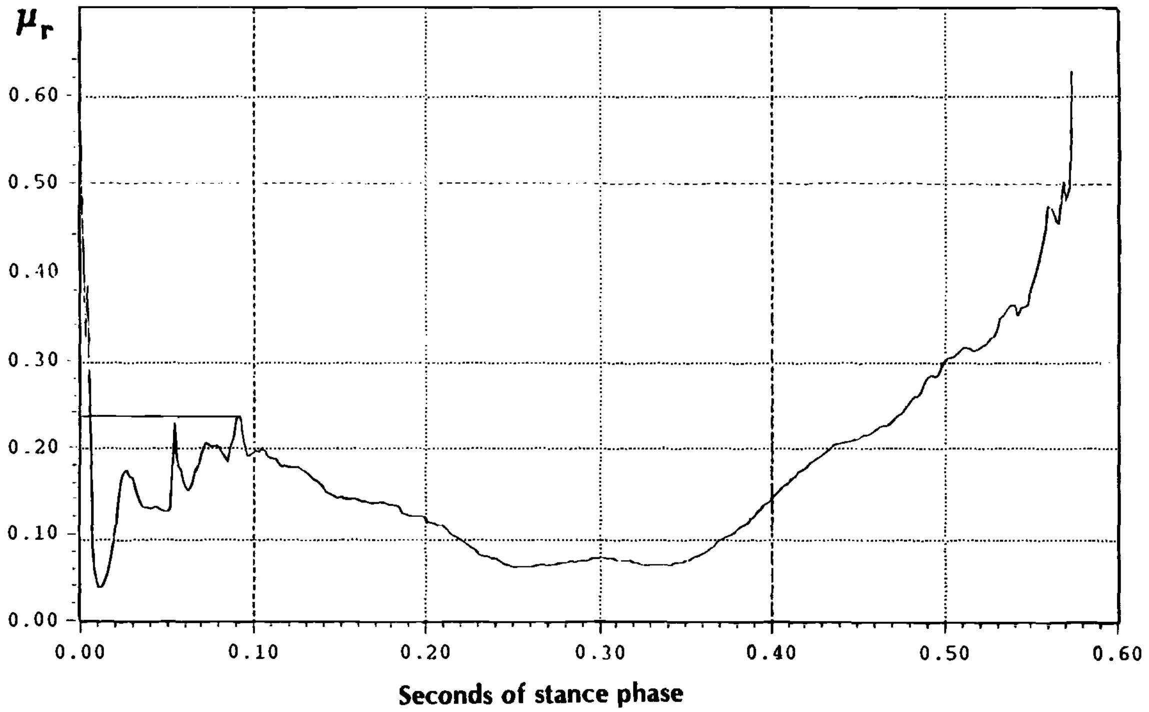

FIG. 1—*μ_r versus time (seconds) during the stance phase for a representative walking trial. Peak μ_r for heel contact is shown during 0.01 and 0.10 s of the stance phase.*

for Footwear. The project conformed to the requirements of the IRB (Institutional Review Board) of Pennsylvania State University for protection of human subjects. Subjects were five healthy male engineering students of normal height and weight[3] without musculoskeletal problems, who wore a size 10 1/2 D shoe. The subjects wore a safety harness to support them if they slipped. They were provided with shoes (brogues or loafers made by Hanover) in which the heel top-piece and outsole were replaced with 6.35 mm (1/4 in.) thick test materials of different Shore A durometer hardness. These materials included styrene-based rubber (SBR), ethylene vinyl acetate (EVA), thermoplastic rubber (TPR), polypropylene, silastic, a standard Neolite® liner, standard leather, an unmodified control brogue, and an unmodified control loafer. A silastic-coated sock simulating the barefoot state, and barefoot walking were also studied.

In successive trials randomized for footwear type, the subjects walked past two photocells located on either end of a Kistler force platform at a series of five or six increasing speeds ranging from moderate to each subject's fastest walking pace. Materials covering the force plate were polypropylene and unpolished vinyl tile. A Kistler force platform (Model 9287, resonance frequency 500 Hz) was used to measure ground reaction force (GRF) components. Force plate output was connected to an electronic amplifier unit, the output signals of which were sampled at 500 Hz. Raw voltages were converted to force values using LABVIEW (National Instruments) software on a Macintosh Quadra 700 computer. Error in GRF measurement by this method is less than 1.5% (11). Curves representing μ_r as a function of time during the stance phase were generated by dividing the vector sum of the anterior-posterior and medial-lateral tangential force by the normal ground reaction force (Fig. 1). Peak μ_r during the interval between 0.01 and 0.10 s of the stance phase was determined. This represents the time of heel contact during which the most dangerous slips occur. Zero/zero artifacts thought to occur during the time interval between 0.0 and 0.01 s were ignored. Relative walking speeds were calculated from the measured time it took the subject to walk the distance between photocells (75.9 cm). The hardness of the shoe outsole sensor materials was measured using the procedures outlined in the ASTM Test Method for Rubber Property-Durometer Hardness (ASTM D 2240-91). A durometer hardness tester, type "A," manufactured by the Shore Instrument Company, Jamaica, NY, was used. Each specimen was "indented" by the durometer at least five times, with the average of the five readings recorded as the hardness value for the material.

To date, data analysis for a single subject from this experiment has been performed and is presented here. Results from this subject have provided a basis for formulating hypotheses that will direct data analysis of additional subjects from this study, as well as future research. Linear regression lines and correlation coefficients (r) were obtained for μ_r versus durometer hardness and walking speed, using DRAW PERFECT software (Figs. 2 and 3). Statistical significance of the correlation coefficients was determined using a t test according to the method described in Colton (12).

Results

A moderate negative correlation was found between peak μ_r and top-piece/outsole hardness ($r = -0.52$, $p < 0.01$) over the range of walking speeds (Fig. 2). These data represented 25 trials (five top-piece/outsole materials at five walking speeds). Mean hardness values for studied materials were: Silastic 46, SBR 53, TPR 61, EVA 62, and Neolite® Test Liner 96.

A fair positive correlation ($r = 0.41$, $p < 0.01$) was found between peak μ_r and walking speed over a range of top-piece/outsole materials: Silastic, SBR, TPR, EVA, Neolite®, Control

[3]The subject whose data are analyzed was a 19-year-old male, height 168 cm; weight 69.7 kg.

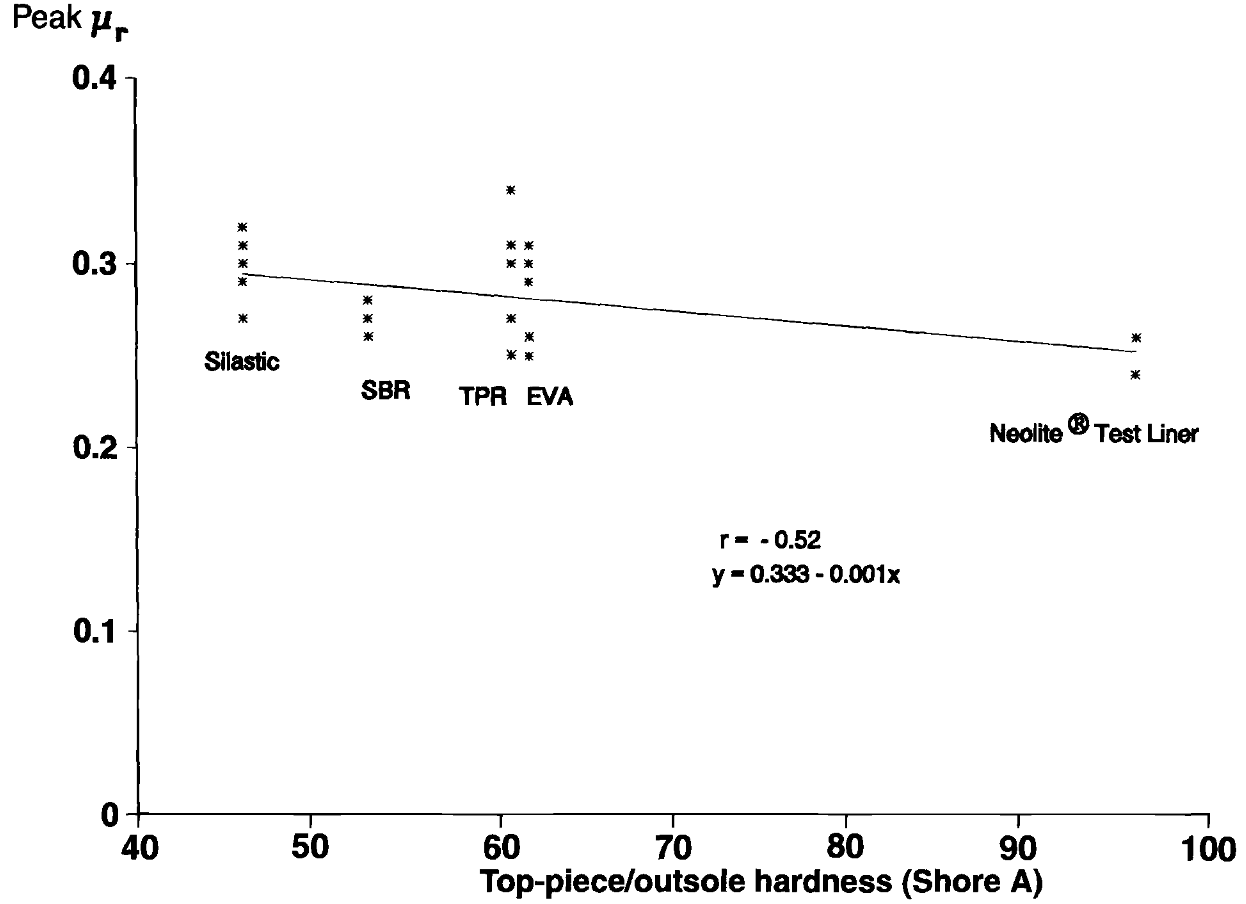

FIG. 2—*Peak μ_r versus top-piece/outsole hardness (Shore A) for a representative subject. Data represent 25 trials with 5 top-piece/outsole materials of various hardness values, each at 5 walking speeds: Silastic 46, SBR 53, TPR 61, EVA 62, Neolite Test Liner 96.*

lace up, Control loafer, Silastic Coated Sock (Fig. 3). These data represented 39 trials (four to five progressive speeds in shoes with each of eight test materials).

Discussion

Data Interpretation

The data suggest that, for this subject, μ_r may be significantly affected by top-piece/outsole hardness and by walking speed, although the found correlations were only fair to moderate. Clearly, results obtained for a single subject cannot be generalized to the population from which the subject was drawn. Also, it should not be inferred that μ_r would vary in the same manner if other footwear materials were used that might have the same hardness values as those investigated here. Many variations of each type of footwear material are possible depending on additives such as fillers and plasticizers. The authors believe the variability in the data presented here represents biomechanical adaptations of the subject, including adjustment of stride length, to all characteristics of the specific footwear, such as design, fit, sole resiliency and flexibility. Ground reaction forces, and thus μ_r, can be quite different for each of several subjects wearing the same shoes (even walking at comparable speeds), since people alter gait and motion based on individual characteristics. Nigg (13) discussed subject variability in relation to dynamic factors and boundary conditions that influence load on the human body during running. Such factors are also pertinent to walking. Thus limb velocity, posture, and muscular activity, as well as anthropometric characteristics, shoe and walkway-surface characteristics and subject perceptions, will determine the balance of forces at each walking speed, and the resulting biomechanical adaptations.

Slip Probability versus μ_r/μ_a

Historically, it has been thought that slips will occur only if $\mu_r/\mu_a > 1$. Problems with application of this concept become evident in reviewing the second phase of a study by Kulakowski et al. (5,6). In that study, the slip frequency of five able-bodied male subjects who walked across detergent-wetted surfaces was related to the ratio μ_r/μ_a (Fig. 4). The purpose of the study was to determine if calculated μ_r could be used together with tribometer results for μ_a to predict the occurrence of slips.

μ_r (the ratio of the resultant of anterior-posterior and medial-lateral ground reaction forces to the normal force) was determined in the Kulakowski et al. study (5,6) by having subjects walk at fast speeds (1.84–2.03 m/s) over a clean force plate. The shoes worn by each subject differed in their outsole material and tread pattern. (The shoe-types worn were: Braune soft shoes, CAGM soft-sole walking shoes, Reebok, soft-sole Rockports, and New Balance). To determine μ_r at heel contact and toe-off at the fast speeds, each subject performed three baseline trials on the clean force plate. Then, wearing the same shoes, the subjects again walked at fast speeds (1.82 to 2.07 m/s) three or four times over detergent-wetted surfaces (5, Vol. II, pp. 142–6). The surfaces wetted with detergent included galvanized steel ($\mu_a = 0.69$), rubber

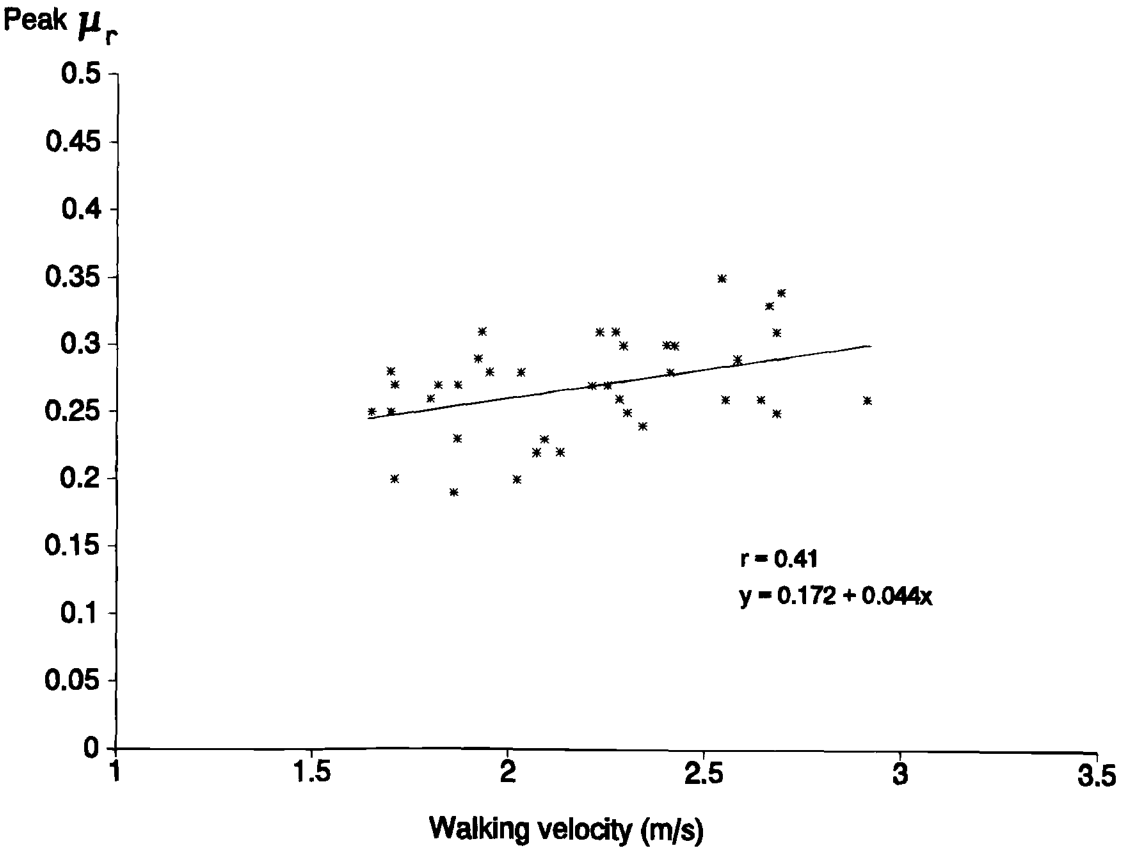

FIG. 3—*Peak μ_r versus walking velocity for a representative male subject. Data represents 39 trials walking at 4–5 progressive walking speeds in shoes with a variety of top-piece outsole materials: Silastic, SBR, TPR, EVA, Neolite, Control loafer, Control lace up shoe, Silastic sock.*

mat (μ_a = 0.26), and the reverse side of linoleum (μ_a = 0.18). These surfaces were chosen because they had static μ_a values below some of the μ_r peaks for the baseline walking trials. μ_a of these detergent-wetted surfaces was measured by an NBS Brungraber tester equipped with a rubber sensor (5, Vol. I, p. 55). The frequency of heel and toe slips was observed for the trials on each walking surface.

Figure 4 shows the frequency of slips observed as a function of μ_r/μ_a for the given subject-surface combinations reported in the study by Kulakowski et al. (5, Vol. I, pp. 111–3). The 30 points shown in the figure represent slip frequencies based on 92 subject observations. Four subjects made three trials on three surfaces. One subject made three trials on two surfaces and four trials on one surface. Both heel and toe peak required friction, and slips, were recorded for each trial (see also 5, Vol. II, pp. 144–6, and pp. 242–3). Slipping became much more probable as the ratio μ_r/μ_a exceeded unity. For measured ratios less than unity, slipping was possible, but less likely. Ten of the 30 points in Fig. 4 did not fit the ideal slipping model (slip will occur only if $\mu_r/\mu_a > 1$). Of note, is the fact that one subject did not slip despite a ratio of μ_r/μ_a of almost 3/1, while one subject did slip despite a ratio of about 0.75/1. No statistical analysis was reported for this data. With reference to the data in Fig. 4, Kulakowski et al. state (6, p. 239):

> The unexpected results were most likely caused by variations in the foot peak forces applied by the same subjects in different trials. Also the thickness of the water film covering the surfaces was likely to vary from test to test, which would affect the available coefficient of friction. It should also be noted that despite instructions, the subjects may have modified their gait in anticipation of the slippery surface and thus may have consciously lowered the required friction in comparison to trials when the surface was known to be dry.

It is noteworthy that, while Kulakowski et al. (5, Vol. II, p. 242) lists the μ_a values (presumably *average* values) for each detergent-wetted surface used in the validation trials, the *range* of μ_a values for these surfaces is not stated. The authors of that study recognize, however, with reference to tribometric testing of μ_a, that long residence times can cause sticking between the tester sensor and a wet surface, and that the NBS Brungraber tester sometimes had this problem even on detergent-wetted surfaces (5, Vol. I, p. 55). Sticking of the tribometer sensor results in artificially high measured values for μ_a, and may invalidate average μ_a values.

Slip-Resistance Guidelines

To develop adequate slip-resistance safety thresholds for μ_a in association with specific tribometers, it is crucial to understand the relationship of slip probability to the ratio of μ_r/μ_a. μ_r, with its apparent dependence on shoe characteristics (such as top-piece/outsole hardness), and on gait, is a major factor in this relationship. How the subject-shoe-surface interaction influences results such as those reported by Kulakowski et al. (Fig. 4) deserves careful study. The subject's gait and his or her shoes, the walkway surface and contaminants, as well as tribometer operation, design, and sensor material are all important in assessing slip probability. Fendley, Marpet, and Medoff have previously reviewed various friction

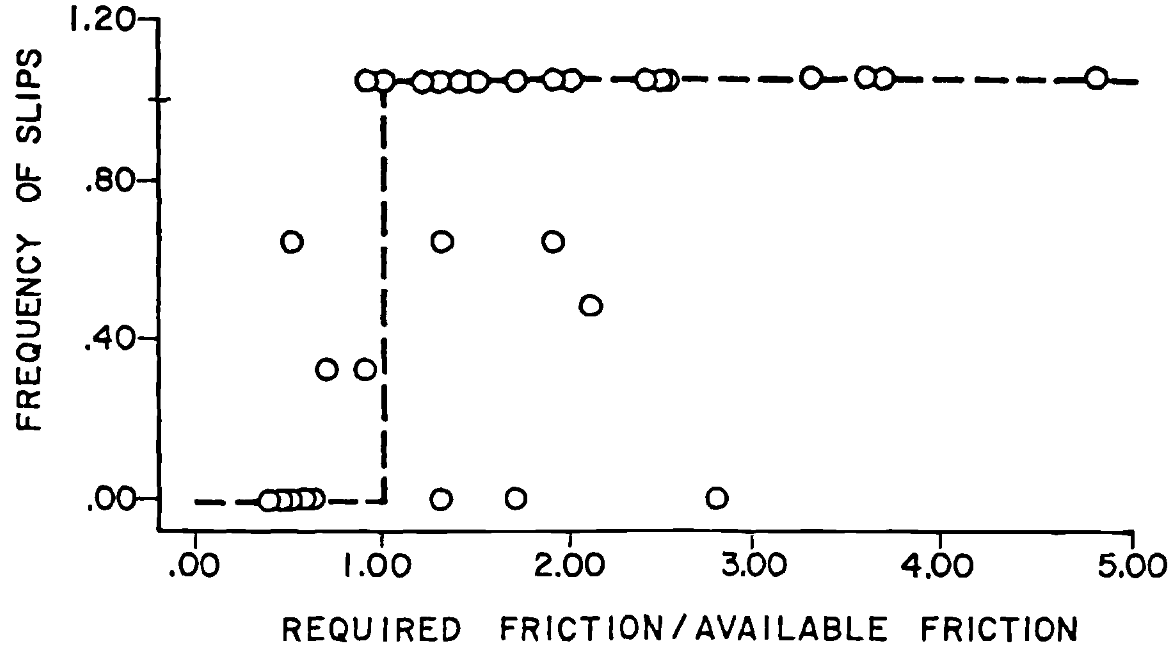

FIG. 4—*Frequency of slips versus the ratio of required over available friction. Reproduced with permission of the publishers (6).*

models of current theoretical and practical importance, and discussed factors vital for slip-prediction (14–16). As a result of disparate friction mechanisms, friction between resilient materials or rubber-like substances cannot be directly compared to friction between hard surfaces. In addition, friction between wet surfaces cannot be directly compared to friction between dry surfaces. Also, especially on contaminated surfaces, roughness of interacting top-piece/outsole materials and walkway surfaces is an important variable in establishing friction. (Of concern in the use of a specific tribometer is whether its sensor, operating pressure, and residence time yield results for a given walkway that can be generalized to what pedestrians would experience wearing footwear of a different material under a different contact pressure.)

The ASTM Test Method D 2047 specifies 0.5 as the minimum static μ_a, measured by the James machine, (using a standard leather sensor), for a nonhazardous (slip-resistant) walkway surface. These authors know of no published accident statistics underpinning this standard. Sacher (17) has reviewed the history of the 0.5 static μ_a slip-resistance value. This threshold was based on feedback to Underwriters Laboratories from polish manufacturers who believed the value to represent adequate safety from their experience with floors in use at the time. Sacher states that the standard has traditionally applied to normal walking at an average pace of three miles per hour on a clean, dry surface. Of note, however, is that ASTM Test Method D 2047 does not restrict application of the 0.5 static μ_a standard to walking at normal speed. It is also worthwhile to note the common mistake of representing particular μ_a value (e.g., 0.5) as the slip-resistance characteristic of a particular surface or outsole material. μ_a represents the interaction between *two* surfaces (e.g., outsole/walkway or tribometer-sensor/walkway). When a specific value is cited, both surfaces must be specified.

Questions have been raised as to the adequacy of the 0.5 static COF slip resistance standard for fast walking conditions and for the mobility disabled. Based on a small experiment, Ekkebus and Killey (7), using an analogy between the geometry of the walking human with the geometry of the James machine, deduced that the 0.5 static μ_a was adequately safe. The authors studied 16 subjects walking at unspecified speeds in unspecified footwear. They found that the tangent of the apex angle which the forward leg made with the vertical (equivalent, in their concept, to μ_r) ranged from 0.298 to 0.437. However, it can be inferred that the Ekkebus and Killey subjects were walking slowly. Average step lengths calculated from subject data of Ekkebus and Killey, 66.8 cm (26.3 in.) for men and 55.9 cm (22 in.) for women, were considerably less than the average step lengths, 78 cm (30.7 in.) for free walking men and 66.5 cm (26.2 in.) for free walking women calculated from studies of 60 men and 30 women by Murray et al. (18,19). In general, stride length increases with walking velocity (20), (although there is a range of step frequencies, and thus stride lengths, for a given walking velocity). James (8) recognized, on the basis of a simple geometrical model of walking similar to that of Ekkebus and Killey, that for increased stride lengths, COFs of greater than 0.5 may be required. He deduced that "a level of friction which is adequate for a normal step of about 60 cm is not adequate if the stride length is increased, whether deliberately or inadvertently" (8, p. 93). To allow for this, he stated, "the minimum level of friction should be set at that required for the maximum stride envisaged, say 0.6 for a 90 cm step."

Indeed, the work of Kulakowski et al. (5) contains data showing the maximum static μ_r required by some subjects exceeded 0.5. μ_r for able-bodied subjects ranged from a low of 0.20 for slow touchdown to a high of 0.86 for fast push-off (5, Vol. II, p. 233). A separate report of this work of Kulakowski and colleagues by Buczek et al. (9) stated μ_r near touchdown for mobility-disabled persons to be 0.64 ± 0.19.

Wilson described an investigation at SATRA where μ_a, determined with the SATRA slip tester, was related to the hardness of top-pieces for a variety of materials (10). The SATRA slip test measures H/V, the horizontal/vertical forces during medium speed dynamic friction testing, with parameters that somewhat mimic normal walking. SATRA has recommended safety guidelines for hardness of top-pieces (Fig. 5). They correlated friction assessments by the SATRA slip tester with wear assessments of slipping

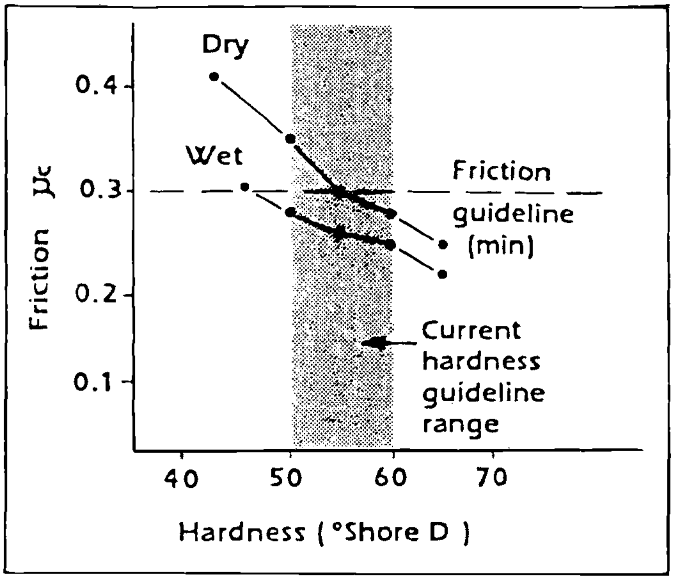

FIG. 5—*Friction versus hardness of women's top-pieces. Reproduced with permission of the publishers (10).*

for various sole materials on wet surfaces. Wilson stated that 0.3 was taken as "an arbitrary pass level (a typical H/V achieved in walking)," citing the work of Perkins (21). It should be noted, however, that in Perkins's study, where eight subjects walked at *normal speed* across a force plate, 0.3 was the *average* peak H/V for the take off phase, whereas the maximum peak H/V's during landing (where top-pieces would be involved) were 0.33 and 0.38. (Wilson (10) showed correlations of SATRA slip-tester measurements with the VTI friction index described by Lanshammer and Strandberg (22). To determine this index, subjects walk as fast as possible around a triangular path without slipping. The time taken is then a measure of tendency to resist slipping.)

Biomechanical Adaptations

The instantaneous ratio of tangential/normal ground reaction forces, μ_r, will be affected by biomechanical adaptations of a subject to particular footwear/walkway-surface combinations. For example, outsole flexibility may influence stride length and thus μ_r. Hardness of floors has been demonstrated to influence the profile of lower extremity muscle activity (23), and thus can affect gait. For these reasons, it cannot be assumed that μ_r measured on a dry force plate would be the same as μ_r for a subject walking on an unrelated and/or detergent-wetted surface of different resiliency. The kinetics and kinematics of walking differ as subjects adapt to various aspects of footwear and walkway surfaces. Several investigators have studied the influence of footwear on the biomechanics of locomotion. Robbins and associates have described sensory attenuation induced by modern athletic footwear (1). Robbins has also demonstrated an effect of footwear midsole hardness on proprioception and stability in older men (2). Effects of footwear properties on ground reaction forces, studied especially in relation to running, may also be important for walking. Nigg et al. (4) found that midsole hardness did not change the magnitude of normal ground reaction forces, but did change the point of application of these forces relative to the foot. Kaelin et al. (24) showed in subject tests that soft outsoles increased impact forces relative to hard outsoles. This was in contrast to material tests which showed greater impact forces for hard outsoles.

Outsole material and pattern are known to affect μ_a (10). Results found thus far in the present pilot study suggest that, through biomechanical adaptations of the subject, top-piece/outsole hardness as well as gait also affects μ_r, and thus the ratio of μ_r/μ_a. μ_r/μ_a in turn affects slip propensity. The relationship of μ_r versus walking speed, and associated slip propensity, for individual top-piece/outsole materials in the study described here, is the subject of a separate paper by Fendley and Marpet (submitted for publication to ASTM).

Conclusion

The μ_r of a single subject was found to have a moderate negative correlation with top-piece/outsole hardness, and a fair positive correlation with walking speed. If the ratio of μ_r/μ_a affects slip propensity, the influence on μ_r of gait and footwear material properties, such as hardness, should be considered in the development of slip-resistance standards for specific tribometers and sensors. Traction/safety determinations for materials should not be based solely on material tests of μ_a. Biomechanical adaptations of the walking subject to the shoe materials, design and fit, are thought to account for variability in the data presented here. Top-piece/outsole hardness may affect other characteristics of footwear such as forefoot flexibility, which may in turn affect stride length and gait dynamics, and thus the instantaneous ratio of tangential to vertical forces, (μ_r).

Acknowledgments

This work was supported in part by a grant from The Pennsylvania State University, and by members of the ASTM Committee F-13 on Safety and Traction for Footwear. The authors are grateful to the Pennsylvania State University Center for Locomotion Studies for use of its facilities.

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