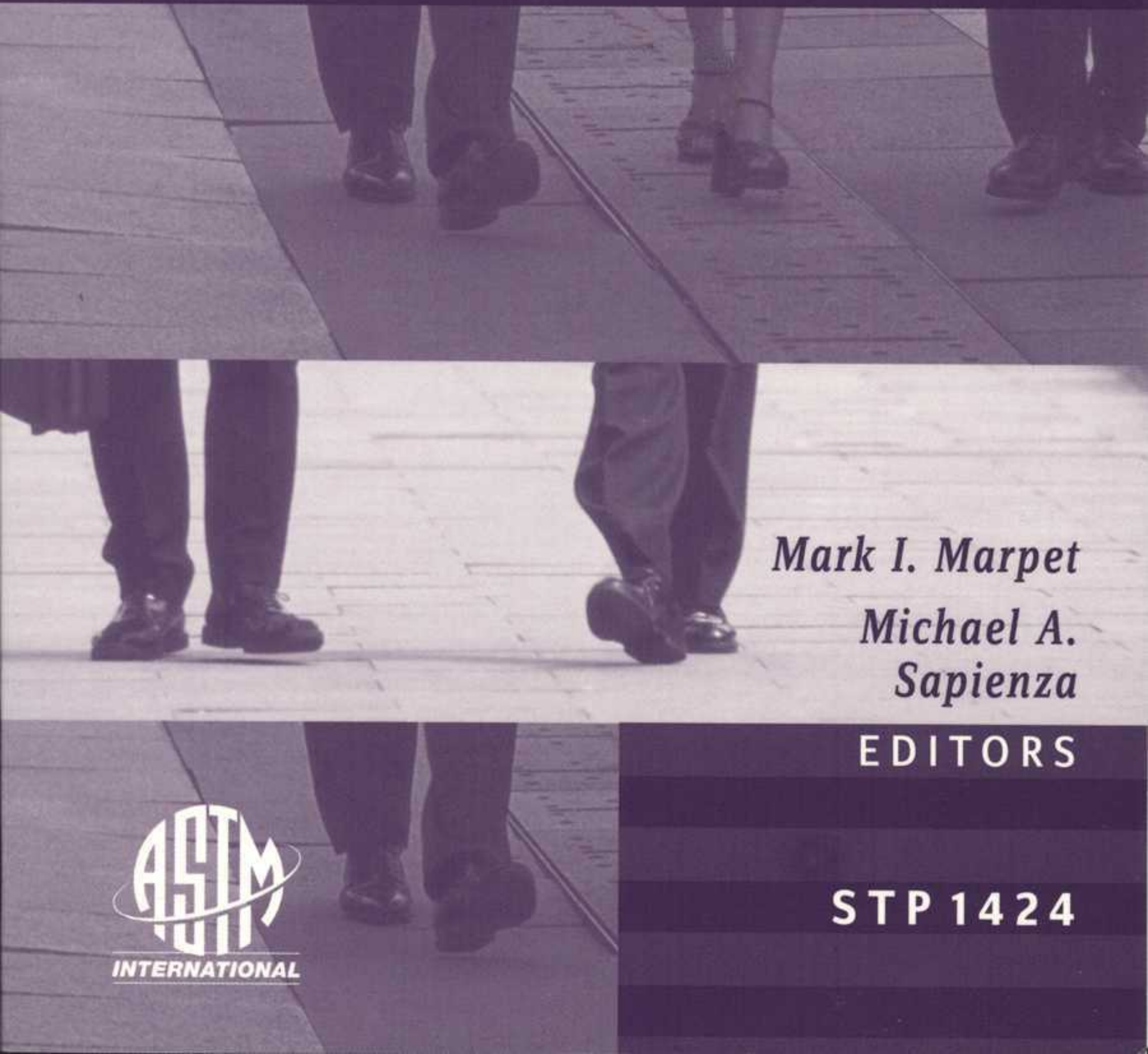
METROLOGY OF

Pedestrian Locomotion and Slip Resistance



Mark I. Marpet
Michael A. Sapienza
EDITORS

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Metrology of Pedestrian Locomotion and Slip Resistance

Mark I. Marpet and Michael A. Sapienza, editors

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Foreword

The Symposium on Metrology of Pedestrian Locomotion and Slip Resistance was held at the ASTM Headquarters, West Conshohocken, Pennsylvania, on 5 June, 2001. ASTM International Committee F13 on Safety and Traction for Footwear served as its sponsor. The symposium co-chairmen and editors for this publication were Mark I. Marpet, St. John's University, and Michael A. Sapienza, Congoleum Corporation.

Contents

Overview vii

BIOMECHANICS OF AMBULATION

Influence of Age and Gender on Utilized Coefficient of Friction during Walking at Different Speeds—JUDITH M. BURNFIELD AND CHRISTOPHER M. POWERS 3

Assessment of Slip Severity Among Different Age Groups—THURMON E. LOCKHART, JEFFREY C. WOLDSTAD, AND JAMES L. SMITH 17

A Critical Analysis of the Relationship Between Shoe-Heel Wear and Pedestrian/Walkway Slip Resistance—IN-JU KIM AND RICHARD SMITH 33

WALKWAY-SAFETY TRIBOMETRY

Variable Inclinable Stepmeter: Using Test Subjects to Evaluate Walkway Surface/Footwear Combinations—H. MEDOFF, R. BRUNGRABER, C. HILFERTY, J. PATEL, AND K. MEHTA 51

An Analysis of the Sliding Properties of Worker's Footwear and Clothing on Roof Surfaces—HISAO NAGATA 58

Comparison of Slip Resistance Measurements between Two Tribometers Using Smooth and Grooved Neolite®-Test-Liner Test Feet—H. MEDOFF, D. H. FLEISHER, AND S. DI PILLA 67

Examination of Sticktion in Wet-Walkway Slip-Resistance Testing—ROBERT H. SMITH 73

WALKWAY-SAFETY STANDARDS DEVELOPMENT

What is Needed to Gain Valid Consensus for Slip Resistance Standards— ANN E. FENDLEY 89

Issues in the Development of Modern Walkway-Safety Tribometry Standards: Required Friction, Contextualization of Test Results, and Non-Proprietary Standards—MARK I. MARPET 96

Implications for the Development of Slip-Resistance Standards Arising from Rank Comparisons of Friction-Test Results Obtained Using Different Walkway-Safety Tribometers Under Various Conditions— RICHARD BOWMAN, CARL J. STRAUTINS, PETER WESTGATE, AND GEOFF W. QUICK 112

Overview

Background

Fall accidents rank number one or two (depending upon what statistic one is using) in the harm, e.g., cost of injury, number of deaths, etc., from accidental causes. Researchers have estimated the cost of slip-precipitated accidents in the billions of dollars per year; there is evidence that slip accidents may be underreported; and it is expected that the number, cost, and harm from slip accidents will rise in the United States as the population ages. Fall accidents that occur as a result of not enough friction available between the floor and shoe bottom for the pedestrian to ambulate without slipping are responsible for a great number of walkway accidents. For this reason, characterizations of how much friction pedestrians require to ambulate and how much friction is available between the foot or shoe bottom and the walkway surface are of great import.

On June 5, 2001, ASTM International's Committee F-13 on Safety and Traction for Footwear sponsored a Symposium on the Metrology of Pedestrian Locomotion and Slip Resistance. It was held at ASTM International headquarters in West Conshohocken, Pennsylvania. Michael Sapienza and I co-chaired that symposium.

The focus of the Symposium on the Metrology of Pedestrian Locomotion and Slip Resistance is clearly spelled out in its name. The objective of the symposium was to gather the latest research findings concerning both how much friction pedestrians require during ambulation and how to measure best the friction available between the walkway surface and the shoe bottom. In the past, a number of symposia and two STPs have covered this and nearby ground.[1] Since these STPs have been released, there have been many significant developments in the areas of locomotion biomechanics and of walkway-safety tribology. Thus, it is time to take stock again. The stated objective in the symposium's call for papers, Sapienza wrote, was—

> to improve pedestrian safety by increasing the current understanding of slip resistance measurements, standards, and criteria, and their application to pedestrian locomotion. This symposium [will] present the latest findings and most up-to-date information on related areas, to focus on directions for future research, to discuss the need for consensus performance criteria, and to review existing information on the causes and prevention of slips and falls. This information will enable the production of meaningful test methods, standards, and practices that will result in a real improvement in pedestrian safety.

At the symposium, twelve papers, from authors around the globe, were presented; a panel discussion was then held. From the twelve presentation abstracts, ten research papers were

[1] Specifically, ASTM STP 649 (Anderson and Senne, Eds., *Walkway Surfaces: Measurement of Slip Resistance* (1978)) and STP 1103 (Gray, Ed., *Slips, Stumbles, and Falls: Pedestrian Footwear and Surfaces* (1990)). These two STPs are must-reads for anyone involved in the friction-related aspects of walkway safety. Related STPs, which may be of real interest to some researchers, include ASTM STP 1073 (Schmidt, Hoerner, Milner, and Morehouse, Eds., *Natural and Artificial Plating Fields: Characteristics and Safety Features* (1990)) and ASTM STP 1145 (Denton and Keshavan, Eds., *Wear and Friction of Elastomers,* (1992)).

written and submitted, made their way through the peer-review and revision process, were ultimately accepted, rewritten yet again, and appear in this STP.

The Papers

These papers explore in considerable depth important aspects of the measurement of pedestrian-locomotion forces (characterized by what is variously called the *required friction,* the *utilized friction,* and the *friction demand*), the measurement of walkway/shoe-bottom friction (the *available friction*), and standards-development issues in walkway/pedestrian safety.

The ten papers fall into those three broad categories: (1) Biomechanics of Ambulation, (2) Walkway-Safety Tribometry, and (3) Walkway-Safety Standards Development.

In the Biomechanics of Ambulation area are three papers: by Burnfield and Powers, by Lockhart et al., and by Kim and Smith. The first two papers explore different aspects of the relationship between age and pedestrian ambulation, significant because fall accidents exact a disproportionate toll on senior citizens. Burnfield and Powers' paper concentrates upon the required friction used by pedestrians of various ages. Lockhart's paper looks at the age-related differences in the way that pedestrians either slip or attempt to recover from a slip. Kim and Smith's paper explores the matter of shoe-bottom wear and its effect upon friction demand; it has significant ramifications in the area of test-foot standardization.

In the tribometry category are four papers. Two of the four, viz., the papers of Brungraber et al. and Nagata, both present novel ways of measuring friction. Brungraber's paper explores the design of a simple, inexpensive ramp that can test the friction available between a whole shoe and a walkway-surface sample. Nagata's paper analyzes the dynamic friction available between a crash-test-dummy roofer surrogate and a sloped roof as a function of the surrogate roofer's acceleration down the roof. The other two papers explore issues in tribometric testing of wet surfaces. Medoff et al.'s paper explores issues in tribometer test-foot design, specifically, the hydrodynamic effects of machining grooves in the test-foot. Here, the authors find that PIAST and VIT instrument results can be made to converge by appropriate test-foot grooving. Smith's paper looks at wet-surface tribology and its relation to a phenomenon that some call "stiction."

There are three standards-development papers. Fendley's paper explores just why it has been *so* difficult to achieve consensus in the development of walkway-safety standards, a difficulty that goes *far* beyond technical issues. My paper discusses both how clinging to too-limiting abstractions of friction can distort the standards-development process, and discusses the rank-comparison approach proposed by the ASTM International Board of Director's Task Group that presently oversees ASTM Committee F-13. This rank-comparison approach is inherently nonproprietary; it will hopefully allow test results from different types of tribometers to be made comparable.

Finally, Bowman et al.'s paper, which explores issues in rank-order comparison of tribometric test results, concludes that the development of a robust ranking system, i.e., one in which rank-orders are preserved across different tribometers and tested materials, is a nontrivial undertaking.

Future Directions

As much as has been accomplished in increasing our knowledge of how and why pedestrians slip and fall, much still needs to be accomplished; these paragraphs could not hope to cover it all.

In the biomechanics-of-locomotion area, there are a number of fruitful areas. Researchers need to continue the work already in progress, including characterizing the friction required for ambulation activities not yet characterized, analyzing age and gender differences not yet analyzed, and honing in on exactly what in the gait determines whether or not a slip-precipitated fall will occur. Work needs to be done in characterizing the friction requirements as a function of the various ambulatory handicaps, e.g., different amputations, physical or neurological conditions, and so forth, and of different ambulatory aids (obviously, these two matters interrelate). This information is needed to ensure that any friction thresholds that are set by standard actually increase pedestrian safety and, at the time, do not needlessly burden the manufacturers of shoes, flooring materials, and floor polishes. Finally, the physical parameters of heelstrike and foot rolldown need to be better characterized, viz., the distribution across time and subjects (including age-, gender-, and impairment-related differences) of horizontal-, vertical-, and angular-foot velocities, the area of shoe-bottom contact, the location of the center of pressure, and the force and pressure distributions.

In the walkway-safety-tribometry area, it would be naïve to think that instrument development has stopped. Importantly, any new tribometric instruments developed need to take into account the important heelstrike and rolldown parameters, many of which are not yet adequately characterized (See the last sentence in the paragraph just above.) Test-foot material, configuration, and preparation issues are actively being worked upon, and need more work. These issues relate to short- and long-term stability of the test feet and procedures to ensure repeatability and reproducibility of results. The statistical analysis of tribometric data is an area ripe for development. Questions abound: is the mean the best summary statistic to ensure pedestrian safety? Should there be a minimum number of test determinations required? One question, the one that Medoff et al.'s paper addresses, is clearly ready for prime time: What is the optimal groove pattern in a given instrument's test foot, to ensure that the test best replicates conditions at the point in the gait cycle where pedestrians are most likely to slip?

In the area of research specifically directed to walkway-safety-standards development, I would like to mention the research and round-robin testing being conducted under the aegis of the Board of Directors F-13 Task Group, chaired by Donald Marlowe. That task group has been and is investigating the rank-order consistency of various test-foot/test-surface combinations. It is a painstaking, time-consuming effort; if successful, it will allow an instrument-independent approach to walkway-safety test-result comparisons.

There is another field that has a potentially large payoff in pedestrian safety. That is in the field of shoe design, which while not discussed in this STP, is certainly under the responsible charge of ASTM Committee F-13 on Safety and Traction for *Footwear* [emphasis mine]. Let me briefly mention two areas that I believe are worth exploring. Firstly, shoe-bottom tread designs that will allow proper drainage of water and other contaminants while operating in a real-world environment, where shoe-bottoms wear, get all sorts of noxious substance on them, have to be affordable, and must not violate fashion constraints. Secondly, it might be fruitful to explore for use as shoe-bottom materials those resilient materials that have an increasing friction with velocity; this could allow the shoe bottom itself to help snub a slip. This is not a new idea: D. I. James discussed this matter in the 1980s.

Disclaimer

The classification of the papers into one of three discrete categories ((1) Biomechanics of Ambulation, (2) Walkway-Safety Tribometry, and (3) Walkway-Safety Standards Development) is somewhat arbitrary because pedestrian/walkway safety is inherently multidisciplinary. Many of the papers in this STP overlap the different categories. Some examples:

- Bowman et al.'s paper was clearly directed towards the need for care in rank-based tribometric-results analysis, so I placed it in the third area. Because of the rich set of experimental results contained in that paper, it could have easily fit into the second.
- Kim and Smith's paper concerning friction changes as a result of heel wear, because of that paper's important implications for tribometer-test-foot standardization, also could have just as easily been placed in the second category.
- Brungraber et al.'s paper, concerning friction measurement using what they call a step ramp, could have easily fit in the biomechanics-of-ambulation category of papers—as it requires humans to step on the ramp to determine if a slip occurs.

The decision concerning which of the three categories each paper best fit rested solely with me. If you disagree with the classification, please do not think ill of the authors, the reviewers, Sapienza, or anyone at ASTM International. Think ill of me.

Similarly, the one- or two-sentence descriptions of the papers above are mine, and not the authors. So if you think they are off the mark ...

If you read all the papers in this STP, you will see that complete agreement between the papers does not exist. For an in-flux research area like pedestrian-walkway slip resistance, that is not surprising. No attempt has been made to eliminate or reconcile inconsistencies or differences between the papers; that is not the reviewer's function; that is not the editor's function. Rather, that is the function of future research and study. The reviewer's function is to ensure that the methodologies and experimental designs are both appropriate and adequately described, that the results are reasonable, and that the conclusions are not overdrawn. The editor's function is to ensure that each paper is drafted in comprehensible American English and that the graphical presentations of information make sense. Thus and importantly, the research and conclusions in the papers in this STP are the authors', and not the reviewers', the editors', or ASTM International's.

Thank You

The Symposium and this STP could not have happened without the contributions of many. I could not possibly name all that were involved without going on for pages. Given that, I would like to thank the symposium presenters, most of whom became authors in this STP. Thank you, participants, authors, and co-authors.

ASTM International and ASTM Committee F-13 on Safety and Traction for Footwear sponsored the symposium. ASTM International allowed us to use their headquarters to hold the symposium. ASTM International is publishing this STP. Thank you, ASTM International.

The difference between magazine articles and research papers is the acted-upon contributions of the peer reviewers. For no apparent reason other than their great expertise in the areas of this symposium and their desire to advance this field of knowledge and endeavor, a gaggle of reviewers were drafted (were volunteered, actually) and pressed into service. (Peer reviewing is a classic example of the maxim that no good deed goes unpunished.) The peer reviewers who worked upon the papers contained in this STP clearly knew the import of an ASTM STP in the walkway-safety area, as evidenced by their careful and *constructive* reviews of the submission drafts. It was the peer reviewers' insights, as acted upon by the authors, that turned the submission drafts into the papers that you see in this STP. Thank you, peer reviewers.

Six need mention by name. I would like to thank Mike Sapienza, the Research Director at Congoleum and my co-chair, who was instrumental and essential in getting the Symposium off the ground. Simply put, without Mike, none of this would have happened. Donald Marlowe was the Chairman of the Board of ASTM International and was and is the Chairman of the Board of Directors Task Group overseeing and supporting Committee F-13's standards-development efforts. Don's support helped get this project off the ground. David Fleisher, who was at the time the chairman of Committee F-13, first suggested the need for this symposium, then *pushed* us to get started, and then gave invaluable assistance to get it off the ground. Mary McKnight at the National Institute for Standards and Technology is a member of ASTM International's Committee on Publications; she investigated the feasibility of our STP proposal and, ultimately, gave us the go-ahead. I know how carefully she re-searched our proposal; by the time I spoke to her, she had literally checked the STP actors and the proposal out with just about everybody who was anybody worldwide in the field of walkway safety. This level of vetting is what gives ASTM STPs their great credibility. Scott Emery at ASTM International painstakingly copy-edited all the papers into proper format, so that the look was both uniform within the STP and similar to other STPs. When Scott got done with the edits to my draft, there was more in the way of notes to the paper than there was paper. The other papers received similar attention. Finally, I would like to thank Crystal Kemp at ASTM International for her help and support. Crystal was my interface with ASTM International's publications group. I could not have asked for a better partner in this endeavor. Thanks, Crystal; I would work with you again in a heartbeat.

Thank you Mike, Don, Dave, Mary, Scott, and Crystal.

Mark I. Marpet
St. John's University, New York, New York;
symposium co-chair and STP editor

BIOMECHANICS OF AMBULATION

Judith M. Burnfield, P.T.,[1] and Christopher M. Powers, Ph.D., P.T.[2]

Influence of Age and Gender on Utilized Coefficient of Friction during Walking at Different Speeds

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Reference: Burnfield, J.M., and Powers, C.M., "**Influence of Age and Gender on Utilized Coefficient of Friction during Walking at Different Speeds,**" *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424,* M. I. Marpet and M.A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: A frequently cited theory suggests that ratio of leg length and stride length (i.e., normalized stride length) can be used to predict the utilized coefficient of friction (COF) during walking. As stride length and leg length differs across persons of different ages and genders, it is probable that utilized COF values also will vary. The purpose of this study was to evaluate the influence of age and gender on utilized COF during non-slip pedestrian gait. Sixty healthy adults were divided into three groups by age (10 males and 10 females in each age group): *Young* (20-39 y.o.); *Middle-aged* (40-59 y.o.); and *Senior* (60-79 y.o.). Ground reaction forces (AMTI forceplate; 600 Hz.) were recorded as subjects walked at slow, medium, and fast speeds. Utilized COF throughout stance was calculated as the ratio of the resultant shear force and vertical force. When collapsed across age groups, females generated higher peak utilized COF values than males at the slow walking speed ($\mu = .24$ vs. $\mu = .20$), while males generated higher peak utilized COF values than females at the fast walking speed ($\mu = .28$ vs. $\mu = .24$). When collapsed between genders, middle-aged subjects generated higher peak utilized COF values at the medium speed than both young and senior subjects ($\mu = .26$ vs. $\mu = .22$ and $\mu = .22$, respectively). At the fast speed, middle-aged subjects generated higher peak utilized COF values than senior subjects ($\mu = .29$ vs. $\mu = .23$). No gender or age related differences in normalized stride length were found. Normalized stride length was a significant predictor of utilized COF, however, only 18% of the variance in utilized COF values could be explained by this factor. These data suggest that while age and gender differences in utilized COF exist, the basis for these differences can not be explained by normalized stride length alone.

Keywords: forensic science, slip resistance, age, gender, speed, gait

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[1] Ph.D. Candidate, Department of Biokinesiology and Physical Therapy, University of Southern California, 1540 E. Alcazar St., CHP-155, Los Angeles, CA 90033.

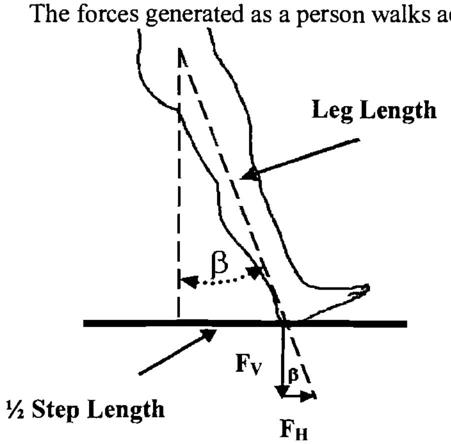
[2] Assistant Professor, Department of Biokinesiology and Physical Therapy, University of Southern California, 1540 E. Alcazar St., CHP-155, Los Angeles, CA 90033.

Introduction

Slipping is a frequent precursor to falls[1-3], and is of significant concern among the elderly due to the increased risk of injury[3-6]. An investigation of occupational injuries to civilian workers over the age of 55 years, reported that slips accounted for more than half (57%) of the falls occurring on level surfaces[6]. In a group of community dwelling older adults (60-88 years old), slips contributed to 38% of falls experienced by men and 17% of falls experienced by women during a one year period[3]. While one out of every three persons over the age of 65 will fall each year[7], falls in older women are of even greater concern due to the heightened risk of fractures in the presence of osteoporosis[8]. As falls are the leading cause of unintentional injuries resulting in death in persons 65 years of age or older[9], an understanding of factors that may contribute to slips and falls is critical.

Causes of falls include both human and environmental factors. During walking, forces generated by the body are transmitted through the foot to the floor. In order to prevent a slip, sufficient friction at the foot-floor interface is required to counteract the shear forces. When the available friction at the foot-floor interface can not meet the biomechanical demands of walking, a slip becomes imminent[10].

The forces generated as a person walks across a given surface can be measured by a force plate and used to calculate the utilized coefficient of friction (COF). The "utilized" COF during walking is defined as the ratio between the shear (resultant of the fore-aft and medial-lateral forces) and vertical components of the ground reaction force (GRF).



$$\text{Utilized COF} = \frac{\textbf{Horizontal Force } (F_H)}{\textbf{Vertical Force } (F_V)}$$

Figure 1 – *Trigonometric calculations used to determine the estimated impact angle (relative to vertical) and to estimate the utilized coefficient of friction (COF) generated during walking [F_V = vertical ground reaction force. F_H = horizontal ground reaction force. β = impact angle (relative to vertical)].*

A frequently cited theory related to the assessment of walkway slip resistance suggests that the angle form by the lower limb at ground impact is predictive of the utilized COF generated during walking[11, 12]. This theory states that the tangent of the angle formed by the lower limb (relative to vertical) at foot impact is equal to the ratio of shear to normal forces at foot strike (Figure 1). This model indicates that, at impact, the angle of the lower limb and the predicted utilized COF would be influenced by two factors: leg length, and step length. Ekkebus and Killey[11, 12] suggested that the most dangerous slip resistance condition would occur when persons with shorter legs

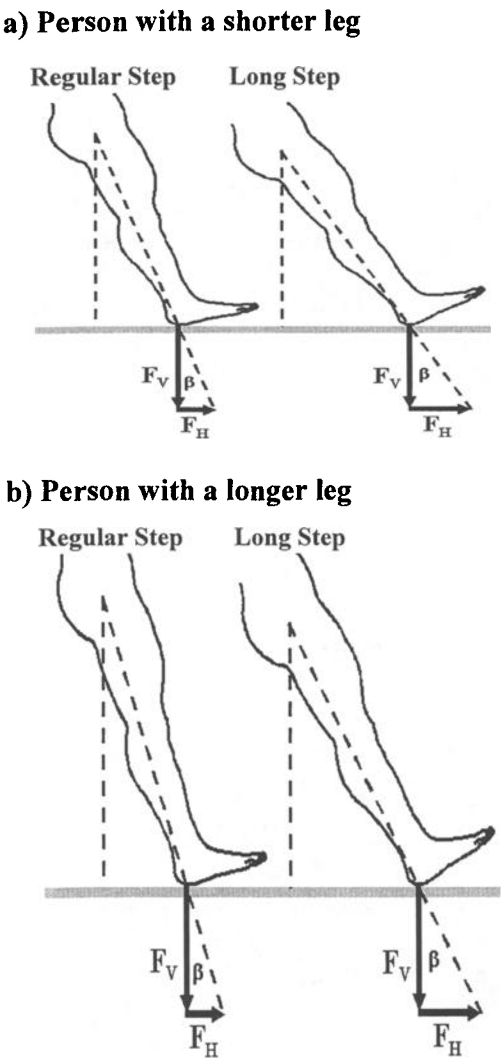


Figure 2 – *Static trigonometric estimations of the utilized COF generated during walking would predict that for a given step length, a greater utilized COF is generated by a person with a shorter leg (a) than a person with a longer leg (b).*

were forced to take a longer step, as the utilized COF requirements would be considerably increased (Figure 2).

As it is well-known that walking characteristics differ across the age spectrum[13-19] and between genders[13, 14, 20], it is probable that utilized COF values also will be influenced by these variables. In healthy adults, gait characteristics such as velocity and stride length remain relatively unchanged until the seventh decade of life[21, 22]. After 60 years of age, reductions in velocity have been documented[21, 22], and occur, in large part, due to decreases in stride length of approximately 7-20% [13, 17, 18, 23, 24]. As stride length decreases with age, static calculations based on these data would suggest that the utilized COF generated by older adults would be less than that generated by younger persons.

It is also well accepted that on the average, women have a shorter leg length than men[25]. There is also research that suggests that at slower speeds, females use a longer stride length than males (normalized to body height) [20], while at faster speeds, males use a longer normalized stride length than females[14, 26]. The potential differences in normalized stride length between females and males at different walking speeds would suggest that the ratio of step length to leg length varies between genders. If at the slow speed, females use a longer relative stride length than males, then the model of Ekkebus and Killey[11, 12] would predict a higher utilized COF for females (Figure 2). Similarly, if at fast speeds males use a longer relative stride length than females, then the model would predict that males would have a higher peak utilized COF than females.

To date, the influence of age and gender on utilized COF values generated while walking at different speeds has not been reported. The purpose of this study was threefold: 1) to quantify age-specific and 2) gender-specific changes in peak utilized COF values during walking at different speeds; and 3) to identify the relationship between normalized stride length and peak utilized COF. It was hypothesized that 1) younger adults would generate higher peak utilized COF values than older adults; 2) at slower speeds, females would generate a higher peak utilized COF values than males, while at fast speeds, males would generate a higher peak utilized COF values than females; and 3) normalized stride length would be a predictor of peak utilized COF. Such information is quite useful for the development of empirically derived standards for walkway slip resistance.

Methods

Subjects

Sixty healthy adults between the ages of 23 and 79 participated in this study. Subjects were divided into three groups: *Young* (20-39 y.o.); *Middle-aged* (40-59 y.o.); and *Senior* (60-79 y.o.). Each group consisted of 10 males and 10 females (Table 1).

Table 1 – *Subject characteristics, Mean (SD).*

Age Group	Gender	Age (yrs)	Leg Length (cm)	Height (cm)	Mass (kg)
Young[1]	Females (n=10)	28.2 (4.8)	87.2 (3.0)	167.1 (6.5)	60.3 (5.9)
	Males (n=10)	28.5 (4.6)	90.8 (3.4)	177.0 (5.5)	81.5 (11.7)
Middle[1]	Females (n=10)	45.9 (5.2)	88.5 (4.3)	160.9 (12.5)	66.7 (10.4)
	Males (n=10)	47.0 (5.5)	95.6 (6.8)	180.8 (6.7)	85.0 (12.8)
Senior[2]	Females (n=10)	69.4 (5.3)	85.6 (5.2)	158.9 (5.1)	60.6 (11.5)
	Males (n=10)	71.4 (5.4)	90.3 (5.3)	169.6 (7.1)	79.6 (13.3)
Total[1]	Females (n=30)	47.8 (17.9)	87.1 (4.3)	162.3 (9.1)	62.5 (9.7)
	Males (n=30)	49.0 (18.6)	92.2 (5.7)	175.8 (7.8)	82.0 (12.4)

[1] Mass, height, and leg length significantly greater for males than females ($p<.05$).
[2] Mass and height significantly greater for males than females ($p<.05$).

Subjects were recruited from the student and faculty population at the University of Southern California (Los Angeles, CA), as well as by word of mouth in the local Los Angeles area. Only persons who were capable of independent ambulation without assistive devices were included. Subjects were excluded if they had a known history of neurologic disease or a lower extremity orthopedic condition that would interfere with walking. This was determined through a medical interview. Prior to participation, each subject was fully informed of the nature of the study, and signed a human subjects consent form approved by the Institutional Review Board of the University of Southern California Health Sciences Campus.

Instrumentation

Ground reaction forces (vertical, fore-aft, and medial-lateral) were recorded using three AMTI force plates (Model OR6-6-1, AMTI Corp., Newton, MA), covered with smooth vinyl composition tile. These force plates were aligned in series and camouflaged within a 10-meter walkway. Force plate data were sampled at 600 Hz, and recorded on a 300 MHz personal computer using a 64-channel analog-to-digital converter.

A VICON motion analysis system (Oxford Metrics Ltd., Oxford, England) was used to measure stride length. Kinematic data were sampled at 60 Hz and recorded digitally on an IBM 166 MHz personal computer.

Procedures

All testing was performed in the Musculoskeletal Biomechanics Research Laboratory at the University of Southern California. Prior to data collection, the length of each subject's right lower extremity (anterior superior iliac spine to medial malleolus) was measured with a soft tape measure during standing. To measure stride length, a reflective marker (20 mm sphere) was then placed over the right lateral malleolus.

Subjects walked in Oxford-style shoes (Iron-Age, Inc., Endwell, New York) that were provided for use during the walking trials. Subjects were instructed to walk at predetermined slow (57 m/min), medium (87 m/min), and fast (132 m/min) walking speeds along the 10-m walkway. Subjects were instructed to look at a spot on the wall at the far end of the walkway to avoid "targeting" a force plate. The middle six meters of the walkway were delineated by photoelectric light switches, which were used to trigger the data acquisition computer. Subjects performed one trial at each walking speed. Walking speed was calculated following each walking trial, and only trials that were within ±5% of the targeted speed, and in which a clean force plate contact occurred (i.e., the right foot contacted one of the three force plates) were accepted. All other trials were repeated.

Data Analysis

Force plate data were analyzed using the VICON Workstation and Reporter software programs (Oxford Metrics, Ltd., Oxford, England). Digitally acquired anterior-posterior, medial-lateral, and vertical forces were exported to ASCII file and imported to an Excel spreadsheet. The anterior-posterior and medial-lateral forces were used to calculate the resultant shear force using the following formula

$$\text{Resultant Force} = \sqrt{(\text{Anterior-Posterior Force})^2 + (\text{Medial-Lateral Force})^2}$$

The utilized COF throughout stance was calculated as the ratio of the resultant/vertical forces. The peak utilized COF value during limb loading, resulting from a shear force that would contribute to the foot sliding anteriorly, was identified. Representative force plate and utilized COF curves for a senior female subject walking at the slow speed are presented in Figure 3. Data were screened for spuriously high utilized COF values resulting from the division of small shear and vertical forces[27]. Typically, non-spurious utilized COF values were observed once the reference limb had been substantially loaded (92 N on the average).

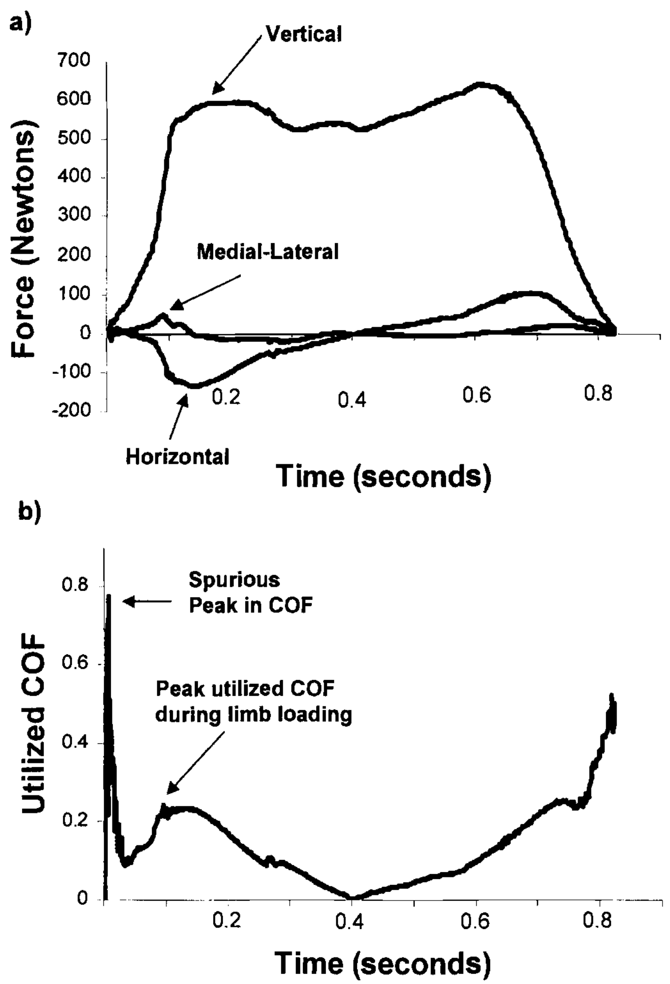


Figure 3 – *Representative tracings of (a) ground reaction forces, and (b) utilized COF during a shod walking trial at the slow speed for a senior female subject. Note that the initial spuriously high spike in the utilized COF was due to a relatively low vertical ground reaction force.*

Kinematic data were analyzed using VICON 370 Workstation software (Oxford Metrics, Ltd., Oxford, England). The reflective marker at the lateral malleolus was identified manually, and three-dimensional marker coordinates were calculated. Stride length was calculated as the horizontal distance, in the direction of progression, of the right lateral malleolus marker from right heel contact to the next right heel contact. Normalized stride length was calculated by dividing each subject's stride length by his/her measured leg length and expressing it as a percentage of leg length.

Statistical Analysis

To determine if utilized COF values varied between genders and across the three age groups, separate two by three analyses of variance (ANOVA) were performed at each of the walking speeds (slow, medium, and fast). A similar analysis was performed for normalized stride length. For each of the two-way ANOVAs performed, if a significant interaction was found, then the main effects were considered separately through post-hoc testing.

To determine if normalized stride length could be used to predict utilized COF, linear regression analysis was performed. All utilized COF values recorded from each subject at each speed were used in this analysis. Statistical analyses were performed using SPSS statistical software (version 10.0; SPSS Inc., Chicago, IL). A significance level of $p < .05$ was used for all statistical comparisons.

Results

Peak Utilized COF

The average peak utilized COF values generated by all 60 subjects at slow, medium and fast walking speeds were μ =.22, μ =.24, and μ =.26, respectively (Table 2). The highest value recorded for a single subject, μ =.44, occurred during a fast walking trial. The lowest value recorded for a single subject, μ =.13, also occurred during a fast walking trial.

Table 2 – *Peak utilized COF values generated during walking at slow, medium, and fast speeds.*

		SLOW		MEDIUM		FAST	
		Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Young	Females (n=10)	.24 (.05)	.20-.35	.24 (.02)	.21-.28	.25 (.04)	.21-.32
	Males (n=10)	.19 (.04)	.14-.30	.21 (.02)	.18-.24	.27 (.03)	.23-.31
Middle	Females (n=10)	.24 (.04)	.16-.28	.27 (.02)	.23-.31	.26 (.05)	.18-.34
	Males (n=10)	.22 (.05)	.17-.33	.26 (.06)	.20-.39	.32 (.09)	.22-.44
Senior	Females (n=10)	.23 (.04)	.14-.30	.22 (.03)	.18-.26	.22 (.06)	.13-.30
	Males (n=10)	.19 (.02)	.17-.22	.22 (.04)	.17-.36	.24 (.06)	.17-.37
Totals by Gender	Females (n=30)	.24 (.04)	.14-.35	.24 (.03)	.18-.31	.24 (.05)	.13-.34
	Males (n=30)	.20 (.04)	.14-.33	.23 (.05)	.17-.39	.28 (.07)	.17-.44
Overall Total	All Subjects (n=60)	.22 (.04)	.14-.35	.24 (.04)	.17-.39	.26 (.06)	.13-.44

When collapsed between genders, the peak utilized COF values varied with age at both the medium (p=.001) and fast (p=.005) walking speeds. At the medium speed, post hoc analysis revealed that the middle-aged subjects generated significantly higher peak utilized COF values than both the young (μ =.26 vs. μ =.22; p=0.001) and senior subjects (μ =.26 vs. μ =.22; p=0.002; Figure 4). At the fast speed, post hoc analysis revealed that the middle-aged subjects generated significantly higher peak utilized COF values than the senior subjects (μ =.29 vs. μ =.23; p=0.018; Figure 4). Peak utilized COF values at the slow speed did not vary across age groups.

When collapsed across age groups, the peak utilized COF values varied between genders. During slow walking, females generated significantly higher peak utilized COF values than males (μ =.24 vs. μ =.20; p=0.002; Figure 4). In contrast, during fast walking, males generated significantly higher peak utilized COF values than females (μ =.28 vs. μ =.24; p=0.023; Figure 4). No difference in peak utilized COF between females and males at the medium speed was observed.

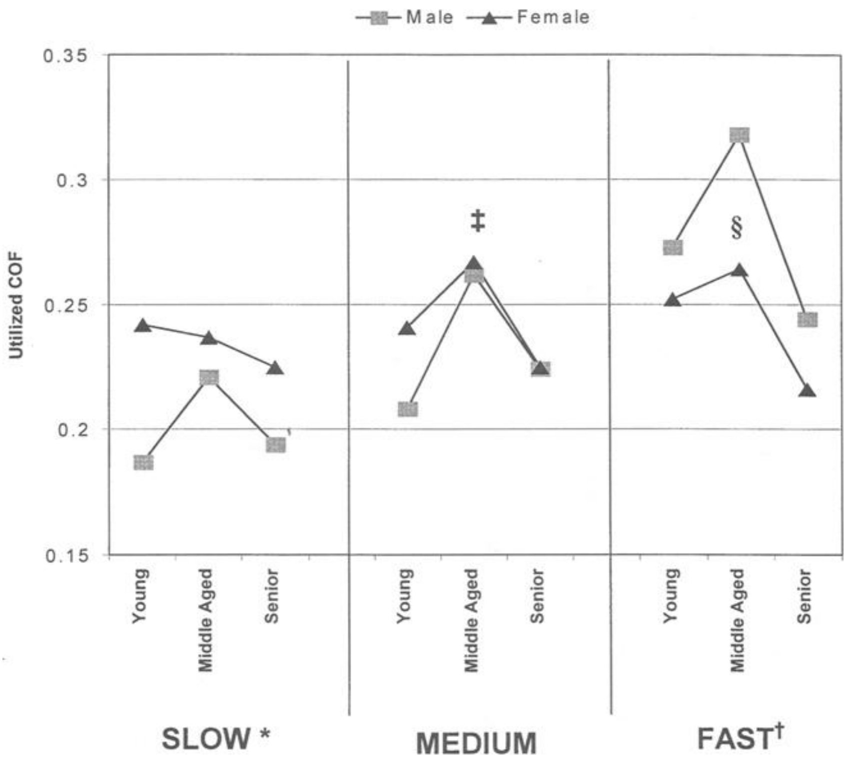


Figure 4 – *Between gender and across age group differences in average peak utilized COF during shod walking at Slow, Medium, and Fast speeds. * = Collapsed across age groups, the average peak utilized COF greater for females than males at the slow walking speed (p=.002). † = Collapsed across age groups, the average peak utilized COF greater for males than females at the fast walking speed (p=.023). ‡ = Collapsed between genders, the average peak utilized COF greater for middle-aged subjects compared to both young (p=.001) and senior subjects (p=.002) at the medium speed. § = Collapsed between genders, the average peak utilized COF greater for middle-aged subjects compared to senior subjects (p=.018) at the fast speed.*

Normalized Stride Length

When collapsed between genders, normalized stride length did not vary significantly among the young, middle-aged and senior groups at either the slow, medium, or fast speeds (Figure 5). When collapsed across age groups, normalized stride length did not vary significantly between females and males at the slow, medium, or fast speeds (Figure 5).

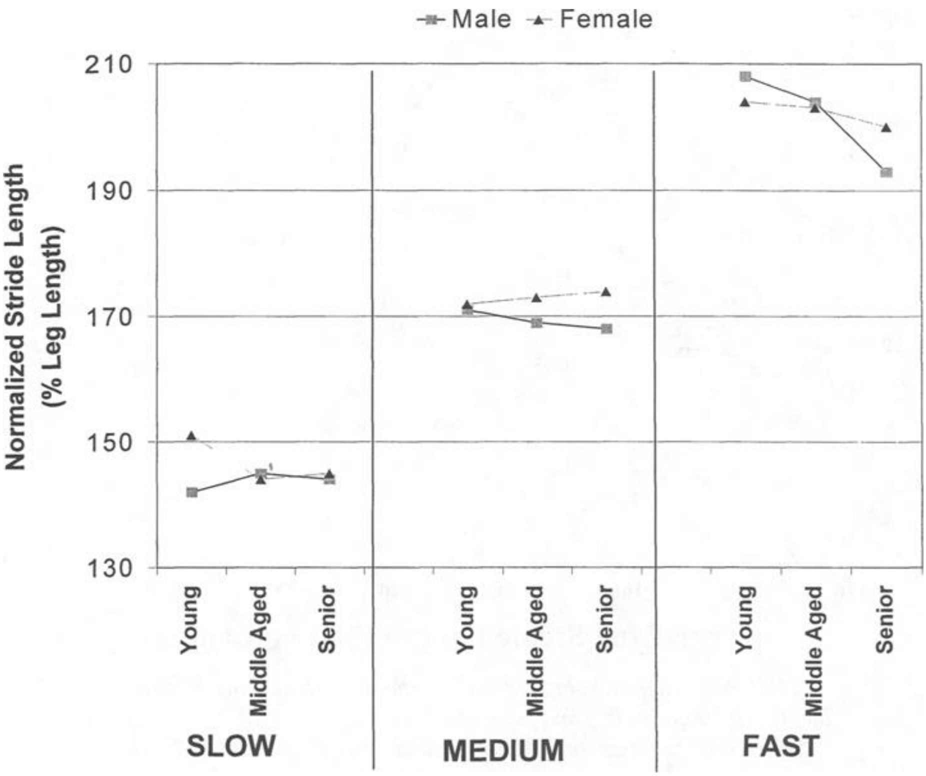


Figure 5 – *Average normalized stride length (stride length/leg length x 100) during shod walking at slow, medium, and fast speeds. No significant differences were observed between male and female subjects or across the age groups.*

Normalized stride length was found to be a significant predictor of peak utilized COF (r = .423; p<.001; Figure 6). However, only 18% of the variance in peak utilized COF values could be explained by normalized stride length (R^2 = .179).

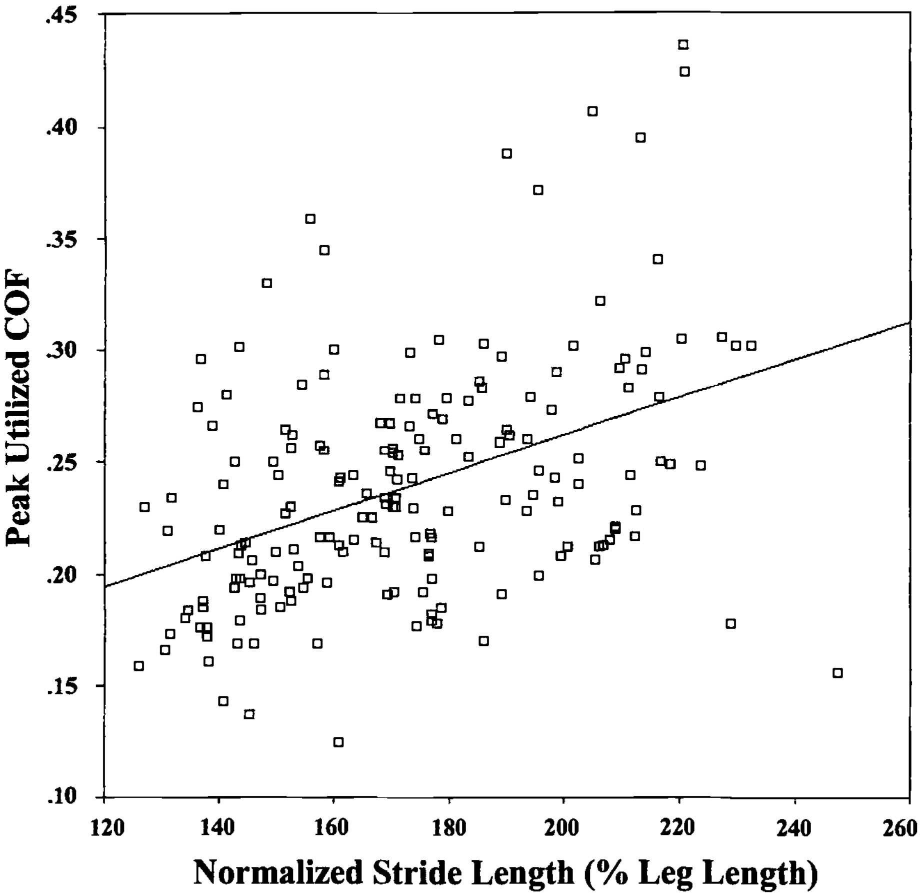


Figure 6 – Relationship between normalized stride length (stride length/leg length x 100) and peak utilized COF across all walking speeds for all 60 subjects (n=180 data points; r=.423; R^2=.18, p<.001)

Discussion

Age or gender related differences in utilized COF values were recorded at each of the three walking speeds. Our initial hypothesis concerning age-related changes in peak utilized COF values was partially accepted as the middle-aged group had higher utilized COF values than the senior group at both the medium and fast walking speeds. However, there were no differences in utilized COF values when the young group was compared to the senior group at any of the speeds, nor was a significant difference identified when the young group was compared to the middle-aged group at the slow speed. Further, the cause of the difference in utilized COF between the middle-aged and senior subjects at the medium and fast speeds could not be explained by normalized stride length as no age-related differences in normalized stride length were observed.

With respect to gender, our initial hypothesis was shown to be correct as females had a higher utilized COF during slow walking and men had a higher utilized COF during fast walking. As with the age-related differences however, the cause of gender-related differences also could not be explained by normalized stride length as no gender differences were observed.

Normalized stride length was found to be a significant predictor of utilized COF, with longer normalized stride lengths being correlated with greater utilized COF values. However, it should be noted that only 18% of the variance in utilized COF could be explained by changes in normalized stride length. This finding suggests that factors other than normalized stride length likely contribute to variations in utilized COF during walking. For example, many physical attributes can influence the mechanics of limb loading such as lower extremity strength, the ability to control the center of mass during weight acceptance, lower extremity joint flexibility, and proprioception (particularly at the knee and ankle). Given the complexity of gait and the neuromuscular system, it is not entirely surprising that only a small portion of utilized COF could be explained by the simple geometric relationship suggested by Ekkebus and Killey[11, 12]. Further research is necessary to determine the degree to which these factors influence utilized COF during walking.

The average utilized COF values recorded for our subjects while walking at slow (μ =.22) and medium (μ =.24) speeds were similar to values reported by Skiba[28] (μ =.21- .23; velocity = 60 to 90 m/min) and Perkins[29] (μ =.22; velocity not reported). Likewise, the average utilized COF value recorded for our young male subjects while walking at a fast speed was identical to the μ =.27 value interpolated (based on a walking speed of 132 m/min) from data presented for a 19 year old male[30].

In contrast to these similarities, our data differed from values reported by Kulakowski and colleagues[31] and Buczek et al. [32]. The utilized COF values reported by Kulakowski and colleagues[31] were greater than the values recorded for our subjects during both slow (μ =.29 vs. μ =.22) and fast (μ =.33 vs. μ =.26) walking, however the apparent trend towards increasing peak utilized COF values with higher speeds was similar between studies. Similarly, Buczek and colleagues[32] reported a higher utilized COF value for five young subjects during level walking (μ =.31 for combined slow and fast walking speeds). Reasons for differences between values recorded in our study and those reported by Kulakowski and colleagues[31] and Buczek et al. [32] likely include differences in footwear, floor characteristics, as well as the limited number of able-bodied subjects studied in the other two studies (n = 5 each).

Finally, in the current study, a wide range of utilized COF values were recorded within each gender and age group. Collapsed across all subjects and speeds, utilized COF values ranged from μ =.13 to μ =.44. Collectively, these data suggest that despite the presence of relatively low mean utilized COF values across the three walking speeds (μ = .22 to .26), wide inter-subject variability exists. As a result of this variability, care must be taken when attributing a specific utilized COF value to a given gender or age group. Further, this variability will likely be important when considering the appropriateness of thresholds used for defining safe flooring. Current recommendations for safe flooring for persons without a disability incorporate a static COF threshold of $\mu \geq .50$ (as measured with the James machine).

Conclusion

While age and gender related differences in utilized COF exist across walking speeds, these differences could not be attributed solely to the selected anthropometric and stride characteristic variables evaluated in this study. The evaluation of the relationship between normalized stride length and utilized COF in the current study revealed that only 18% of the variability in utilized COF values could be explained by normalized stride length. Further, while selected differences in utilized COF between senior and middle-aged subjects were identified, the anticipated differences in utilized COF between young and senior subjects did not emerge as predicted. Collectively, these findings suggest that factors, other than age and the selected anthropometric variables considered in this study, likely play a large role in determining utilized COF values. These factors may include lower extremity strength, proprioception, and range of motion. Additionally, the wide inter-subject variability in utilized COF values demonstrated in this study suggests that minimum threshold levels used to define "safe" walkway surfaces should consider not only average utilized COF values, but also the range of values used by individual subjects.

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Thurmon E. Lockhart, [1] Jeffrey C. Woldstad, [2] and James L. Smith [3]

Assessment of Slip Severity Among Different Age Groups

Reference: Lockhart, T. E., Woldstad, J. C., and Smith, J. L., "**Assessment of Slip Severity Among Different Age Groups,**" *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424,* M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: A laboratory study utilizing new techniques for assessing slip severity was conducted to investigate the process of inadvertent slips and falls among different age groups. Forty-two subjects from three age groups (young adults, middle-aged, and the elderly) walked on a rectangular track at a self-determined pace. Without the subjects' awareness, a slippery floor surface was placed on the track over a force-measuring platform. The results indicated that elderly adults' friction demand (RCOF) was not significantly different from the young and middle-aged adults. The older adults, however, fell more often than the other age groups. Fall recovery threshold (FRT) measures indicated that younger adults were able to recover from a slip (thus preventing a fall) with higher sliding speeds and longer slip distances than older adults. Additionally, older adults' adjusted friction utilization (AFU) on the slippery floor surface was not adjusted within the dynamic friction requirements, resulting in more falls. Based on the age-related differences observed, it appears that fall-related accidents among older adults are due more to factors influencing compensation of a slip rather than gait characteristics influencing slip initiation.

Keywords: Slips and falls; slip severity; fall recovery, gait biomechanics; aging; friction demand; slip distances; heel velocity; coefficient of friction

Introduction

Reducing slip and fall accidents has been a goal of many researchers since the 1920s. Four primary approaches have been traditionally used to understand slip and fall accidents: epidemiology, biomechanics, tribology, and psychophysics. In spite of improvements in tribometric techniques to assess shoe/floor interactions, increased knowledge of the biomechanical responses to walking on slippery floor surfaces, and numerous studies exploring postural control, fall accidents continue to represent a

[1] Grado Department of Industrial and Systems Engineering (0118), 250 Durham Hall, Virginia Polytechnic Institute and State University, Blacksburg, VA.
[2] Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR.
[3] Department of Industrial Engineering, Texas Tech University, Lubbock, TX.

significant burden to society in terms of both human suffering and economic losses. Older adults are particularly at risk. Falls are the leading cause of death resulting from injury among those over 75 years old and the second highest cause of accidental death for 45-75 year olds [1]. Furthermore, with longer life expectancy and increased proportion of the older adults in the overall population, society in the aggregate is likely to experience a greater risk for slip and fall accidents, which may pose additional burden on the health care system [2].

A review of the literature indicates that multiple mechanisms are involved in slip and fall accidents. In general, fall accidents on level walking surfaces are believed to be the result of a loss of traction between the shoe and the walkway surface [3, 4]. The term "slip" has often been used to describe this loss of traction, both when the slip results in a fall and when it does not [5]. Recently, slip classifications have been used as a measure of floor surface slipperiness [6]. The term *slipperiness* has been defined as "underfoot conditions which may interfere with human [ambulation], causing a foot slide that may result in injury or harmful loading of body tissues due to a sudden release of energy" [7]. In addition to interest in slips and microslips as potential indicators of slipperiness, gait parameters (such as required coefficient of friction [RCOF]) at the point of initial foot contact are of interest for tribological studies [8, 9].

Slip behavior has been investigated by many researchers [6, 8, 10]. In terms of the biomechanical approach to the prevention of slips and falls, much attention has been focused on studying of the slip behavior of young individuals. Actual slip experiments were conducted on subjects wearing test shoes, walking from non-slippery surfaces onto slippery surfaces, utilizing a fall arresting rig to prevent injuries. In the majority of experiments, slips occurred in a forward direction having started shortly after the heel contacted a contaminated surface. In some cases the shoe only slipped a few centimeters and then stopped, so that the subjects were able to regain balance and continue walking. In other cases, the foot continued slipping, and the subjects were unable to recover balance. The severity of a slip (whether or not the slip resulted in a fall) therefore, appears to be dependent on the distance that subject's foot slipped (for example, any slip distance more than 10 to 15 cm resulted in loss of balance [10]). Perkins [8] noted that this effect is probably related to the acceleration of the foot as it slips forward. He further noted that if the foot travels faster than the body, the body can never catch up, but if the body is able to overtake the slipping foot, the slip may be able to be arrested.

Although the above concepts are sound and logical, currently there exist no universal definitions (or the robust technique) for assessing slip severity. In other words, there exist no unambiguous methodologies to assess severity of a slip such as slip distance, sliding speeds, and friction utilization during slipping. Strandberg and Lanshammar [11], for example, identified slips by examining the coordinates of the heels. They defined the slip-start point as occurring at the first minimum of the heel's forward velocity; but, they did not discuss how to determine slip-stop point. Perkins [8] did not specify how to determine the slip-start or the slip-stop points. Rather, he presented stroboscopic multi-image photographs of heel slip.

The purpose of this study was to develop a method to assess slip severity among different age groups. This was accomplished by closely examining the slip behaviors of individuals from three different age groups (young, middle-aged, and the elderly), and defining the repeatable gait patterns during the related events of slips and falls. We have also investigated, utilizing new models for assessing slip severity, the process of initiation of and recovery from inadvertent slips and falls among different age groups, taking care so as not to confound our results with safety-harness artifacts. We hypothesize that slip severity (as measured by slip distances, sliding heel velocity, sliding heel acceleration, and adjusted friction utilization) will be greater among older individuals than their younger counterparts.

Experimental Method

Subjects

Fourteen young adults (7 male and 7 female, aged 18-29), 14 middle-aged adults (7 male and 7 female, aged 35-59), and 14 senior citizens (7 male and 7 female, over 65 years of age) participated in these experiments. (Age, height and weight information are presented in Table 1.) The young subjects were recruited from the general student population at Texas Tech University and older subjects were recruited from the local community. Prior to participating in the experiment, older subjects were examined by a physician to ensure that they were in generally good physical health. Subjects also received a peripheral neuropathy examination in the Neurology Department at St. Mary's Hospital in Lubbock, Texas. Subjects were excluded from the study based on these tests or upon the physician's professional judgment. Each participant completed an informed consent procedure approved by the Texas Tech Institutional Review Board. All participants were compensated for their time and effort.

Table 1-Subject information.

	Young Mean (S.D.)	Middle Mean (S.D.)	Old Mean (S.D.)
Age (years)	26 (2.1)	46.9 (13.6)	75.5 (6.8)
Height (cm)	169.7 (6.1)	173.5 (6.3)	170.2 (6.4)
Weight (kg)	68.7 (9.6)	75.5 (16.1)	76.8 (13.3)

Apparatus

Two commonly used floor materials were used in this experiment: outdoor carpet ("Beau Lieu" Olefin) and vinyl tile (Armstrong). The vinyl tile surface was covered with motor oil (10W40) to reduce the coefficient of friction (COF). The available dynamic COF (ADCOF) for each surface was measured using a standard 4.54 Kg (10 lb.) horizontal pull slipmeter with a rubber sole material and found to be 1.80 for the outdoor carpet and 0.08 for the oily vinyl tile. ADCOF measurements were conducted at a constant velocity of 20 cm/sec. Averages of 10 measurements on each of the two floor surfaces were used to characterize the ADCOF values.

Walking trials were conducted on an instrumented rectangular track (Figure 1). Its wooden deck was approximately 6.7 meters x 6.7 meters, permitting a straight walking path (subjects were instructed to walk straight after turning). The entire deck was covered with carpet. A remote controlled floor changer was used to change the test floor surfaces so as to provide unexpected slippery conditions.

The test surfaces (oily vinyl floor tiles) were mounted on a platform that was connected to the force plates (black box on the track- Figure 1). The floor-changing system allowed a subject to walk under experimental conditions without being aware of the floor-surface change. Subjects were also supplied with a Walkman® (listening to old comedy routines) during the walking experiment to conceal the sound of the floor changer's motor.

A fall arresting rig was used to protect subjects from falling during the experiment. The rig consists of a full-body parachute harness attached to a servo-driven overhead suspension arm. A feedback control system allowed the arm to sense the position of the subject and increase or reduce velocity to stay overhead. Additionally, the telescoping boom connected to the arm was programmed to move in and out to allow a straight walking path. The rig was designed to permit the subject to fall approximately 15 cm before arresting the fall and stopping the forward motion.

The ground reaction forces of the subjects walking over the test surfaces were measured using two Bertec force plates sampled at a rate of 600 Hz. An Ariel Performance Analysis System and four Panasonic video recorders, sampling and recording at a rate of 60 Hz, were used to collect the three-dimensional postural data as they walked over the test surface.

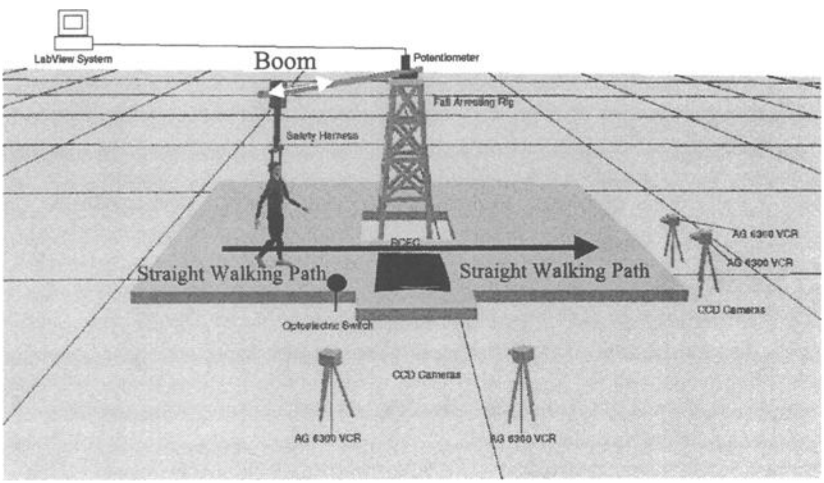

Figure 1 – Experimental setup including fall arresting rig and harness, boom, cameras (4), optoelectric switch, and data collection system. Movement of the boom (arrow) side to side allowed straight walking path after turning.

Procedure

The subjects were scheduled to participate in two testing sessions within one week's time. The subjects attended a familiarization session before the experiment. During the familiarization, the fall arresting system and walking conditions were introduced. Prior to the walking experiment, retro-reflectors were attached to anatomically significant body positions: 26 body markers defined a 14-segment whole body model [12]. Foot segments were analyzed for this study. The heel target was placed on the outer-edge of the shoe (2.4 cm from rear-edge and bottom of the shoe). The target representing the toe was placed 2.5 cm above the sole, on the outer-edge of the foot. During the experiment, the subjects walked across each floor condition for 10 min. While walking, subjects were instructed to focus their eyes on a light emitting diode located approximately 2 meters above and 3 meters away from the testing area. A secondary task that required them to call out when the light was on and when it was off was used to ensure that they attended to the LED. During each of the 10 min sessions, two slippery conditions were randomly introduced by the system, and measurements of subject's posture and ground reaction forces were recorded (second trial was used only if first trial was not robust – i.e., not stepping on the force plate). Location of the slippery surface was randomly distributed by the two floor changers. Standard shoes with rubber soles were supplied to all subjects to reduce COF variability between shoe sole and test-floor surfaces.

Calculations of Dependent Measures

Figure 2 illustrates typical slip parameters over time, starting at heel contact, which we defined as the instant when the vertical ground reaction force (GRF) exceeded 10N. To synchronize kinetic and kinematic variables, an LED was coupled to the vertical force output of the force plates and when the force exceeded 10N the LED was triggered.

Initially, as indicated by horizontal heel positions, the heel does not slip forward considerably (horizontal heel velocity decreases as the heel quickly decelerates during this time period). This is believed to be the result of the position of the whole body COM (closer to the rear foot) [12] during the heel contact phase of the gait cycle. Shortly after heel contact (approx. 60 ms) (as the fore-foot comes down and the whole body COM shifts towards the sliding heel), the heel begins to slip forward considerably. Afterwards, the sliding heel reaches maximum velocity. During this slipping period, the heel accelerates reaching the maximum near the mid-point of the sliding heel velocity profile.

After reaching maximum sliding heel velocity, the sliding heel velocity decreases to the minimum, halting further slipping (not shown in Figure 2).

Slip Distance: Son [13], utilizing the three-dimensional coordinates of the heel reflector, identified the slip-start point at the instant at which the horizontal heel acceleration passed through zero (going from negative to positive, equivalent to the first minimum of the horizontal heel velocity after the heel contact). Son also defined the slip-stop point at the instant the first minimum of the horizontal heel velocity *after* the slip-start point (not shown in figure 2). Son's definitions are much clearer than the others [8, 10]. Alteration of the vertical and horizontal force profiles beyond the point of maximum horizontal heel velocity due to interaction of the test subject with the safety harness is an

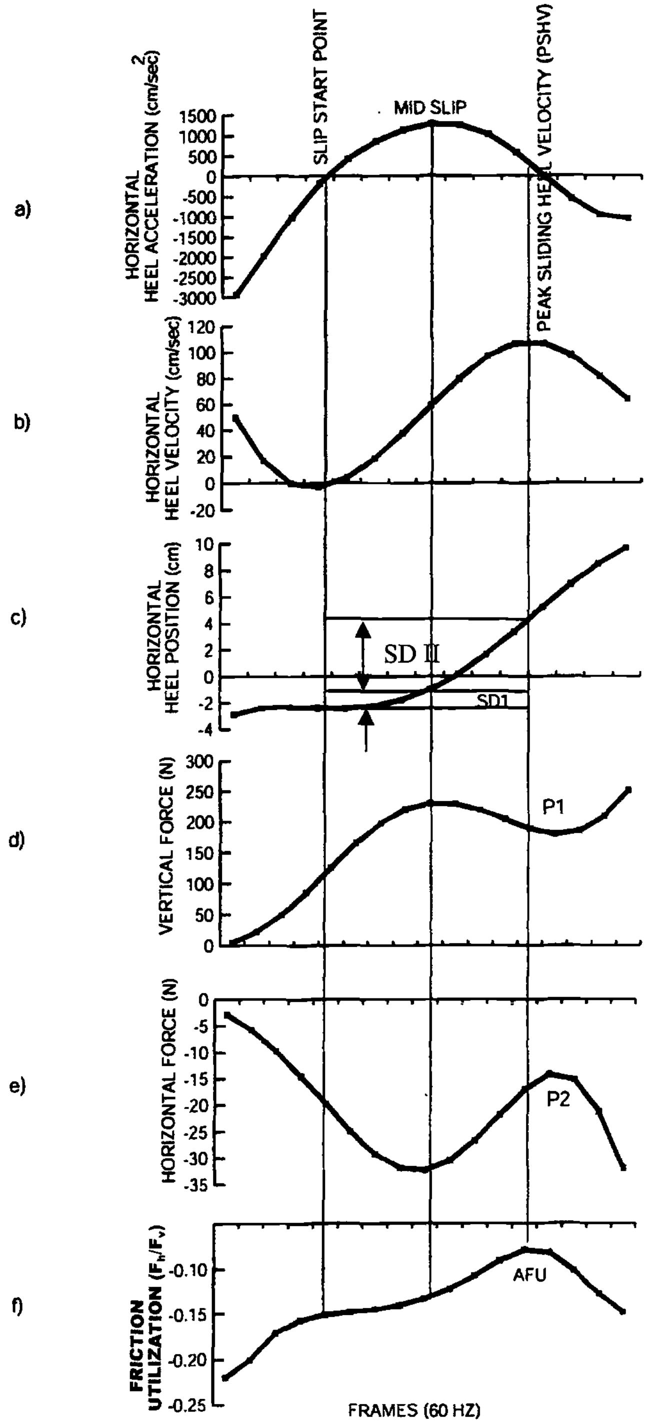

Figure 2. *Composite view of the slip parameters*. Each tick marker represents 1/60 second.

issue that must be considered. Figure 2 illustrates this concept. The vertical force profile (at P1) illustrates that there is a significant decrease in vertical force as the subject slips (after reaching peak heel sliding velocity). This decrease in vertical force may have resulted when the subject tried to compensate for a slip by utilizing the fall arresting harness or by the automatic support given to falling subjects by the harness. In the process, interactions with the harness can affect the horizontal force profile (P2). Thus, beyond the peak heel velocity point, because the fall arresting harness may affect the biomechanical parameters of slip severity (such as slip distance, slipping velocity etc), the use of any metrics that take into account events post-peak-heel-sliding would be problematic. Given that, we have defined two novel slip distances (SD_I and SD_{II}).

Initial Slip Distance (SD_I): the initial distance traveled by the foot after the heel-contact phase of the gait cycle was measured to provide information concerning the severity of slip initiation. The slip-start point (X_1,Y_1) was defined in the same manner that Son defined the slip-start point. The slip-stop point for SD_I (X_2, Y_2), is defined differently. Our slip-stop point occurs at the instant that the peak horizontal heel acceleration occurs *after* the slip-start point (the mid-slip point on Figure 2a). SD_I is calculated using the heel coordinates between slip-start (X_1,Y_1) and slip-stop (X_2, Y_2) points using the Pythagorean distance formula. (See Figure 2c.)

$$SD_I = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \tag{1}$$

Slip Distance II (SD_{II}) was developed to provide information concerning the slip behavior *after* the initiation of slips. The start-instant for the SD_{II} is defined as slip-stop point for SD_I, i.e., mid-slip on Figure 2a. The end point of SD_{II} is the instant where the first maximum of the horizontal heel velocity after slip-start point occurred (seen as the Peak Sliding Heel Velocity [PSHV] in Figures 2a and 2b). SD_{II} was also calculated utilizing the Pythagorean distance formula (1).

Average Sliding Heel Velocity ($\bar{v}_s$): The average sliding heel velocity ($\bar{v}_s$) of the heel after heel contact was calculated by averaging the instantaneous sliding heel velocity (ISHV) starting one frame before the slip-start point and ending one frame after the PSHV point (Figure 2a) and using the formula:

$$ISHV_{k+i} = [X_{(k+i+1)} - X_{(k+i-1)}]/2\Delta t \qquad \text{where, k = slip start point and i = slip frame number} \tag{2}$$

thus,

$$\bar{v}_s = \sum_{i=1}^{N} ISHV_{k+i}/N \qquad \text{where, N = total slip frames} \tag{3}$$

Average Sliding Heel Acceleration (H_{acc}): The average sliding heel acceleration of the heel after heel contact was calculated by averaging the instantaneous sliding heel acceleration between the slip-start and slip-stop points.

Peak Adjusted Friction Utilization (AFU): AFU is the measured ratio (F_h/F_v) of the horizontal foot force (F_h) to the vertical foot force (F_v) at the slip-stop point, and represents the ability to adjust dynamic frictional requirements during slipping [7]. The significance of this ratio is that it indicates when the gait compensation for a slip is most likely to occur. Figure 2 illustrates this concept. In figure 2, as the horizontal heel velocity reaches its maximum, the magnitude of the horizontal force is decreasing (as is the vertical force), and the magnitude of the ratio of the horizontal to vertical force decreases. At that instant, if AFU is higher than the available dynamic coefficient of friction (ADCOF), the heel will continue to increase in velocity; however, on these data, (i.e., figure 2), AFU is lower than the ADCOF, and the heel decelerates (the beginning of halting or controlling a slip.

Step Length (SL): The linear distance in the direction of progression between successive points of foot-to-floor contact of one foot and then the other foot was measured on both the carpet and the oily tile surfaces. The resultant step lengths were calculated from the difference between consecutive positions of the heels contacting the floor using the Pythagorean distance formula (1).

Heel Contact Velocity (v_{hc}): The instantaneous horizontal heel velocity (v_{hc}) at heel contact was calculated on both the carpet and the oily-tile surfaces utilizing heel velocities in the plane of contact at foot displacements of $^1/_{60}$ second (the video-frame time, t_{frame}) before and after the heel-contact phase of the gait cycle.

Friction Demand (RCOF): The required coefficient of friction (RCOF) was obtained by dividing the horizontal ground reaction force by the vertical ground reaction force (F_h/F_v) after heel contact (peak 3 as defined by Perkins [8]) on the carpeted floor surface to obtain the initial friction demand.

Treatment of Data

The converted coordinate data for each of the body markers and the ground reaction forces were digitally smoothed using a fourth-order, zero-lag, low-pass Butterworth filter. The dependent measures: the slip distances (SD_I and SD_{II}), average sliding heel velocity, average sliding heel acceleration, and adjusted friction utilization during slipping, were analyzed using separate one-way repeated-measures ANOVAs with age groups as the independent variable. (Significance was assumed when α 0.05). To test whether or not subjects had an awareness that the floor surfaces had been switched, step length (SL) and horizontal heel contact velocity (v_{hc}) were each analyzed using a separate 2 x 2 (age group x floor surface) repeated-measures ANOVA. RCOF was analyzed using a one-way analysis of variance on the carpeted floor surface.

Table 2 summarizes slip parameters among three different age groups.

Table 2 - Summary of slip parameters among three different age groups.

	Variables	Young Mean (S.D.)	Middle Mean (S.D.)	Old Mean (S.D.)
	Slip Distance I (cm) (SD_I)	1.08 (1.49)	2.30 (1.48)	2.17 (1.37)
*	Slip Distance II (cm) (SD_{II})	4.25 (3.24)	6.25 (3.27)	7.67 (3.48)
*	Average Sliding Heel Velocity (cm/s)	47.34 (9.74)	61.86 (9.17)	75.84 (9.86)
*	Average Sliding Heel Acc. (cm/s^2)	609.50 (79.2)	907.80 (73.5)	912.10 (66.6)
*	Peak Adjusted Friction Utilization	0.074 (0.01)	0.10 (0.01)	0.12 (0.01)
*	Step Length (cm)	65.35 (7.34)	67.63 (9.05)	59.12 (7.67)
	Heel Contact Velocity (cm/s)	31.03 (14.5)	32.11 (13.5)	42.31 (17.9)
	RCOF	0.176 (0.01)	0.188 (0.02)	0.192 (0.02)

* Statistically Significant ($p \leq 0.05$).

Results

Slip Parameters

The results of a one-way ANOVA on SD_I indicated no statistically significant differences between the age groups ($F_{(2,39)} = 2.989, p \approx 0.06$).

The results of a one-way ANOVA on SD_{II} indicated significant differences with respect to age group ($F_{(2,39)} = 3.69, p \approx 0.034$). Tukey-Kramer post-hoc tests indicated that the older age group's SD_{II} was significantly longer ($p \approx 0.0001$) than both the young- and middle-age groups, and that there were no significant differences between middle- and older-age groups.

The results of a one-way ANOVA on average sliding heel velocity ($\bar{v}_s$) indicated that there were significant differences in this parameter as a function of age group ($F_{(2,39)} = 5.536, p \approx 0.007$). Tukey-Kramer post-hoc tests indicated that the older age group's $\bar{v}_s$ was significantly faster ($p \approx 0.0001$) than younger-age group. No statistically significant differences were found between the middle-age and older-age groups. (See Figure 3).

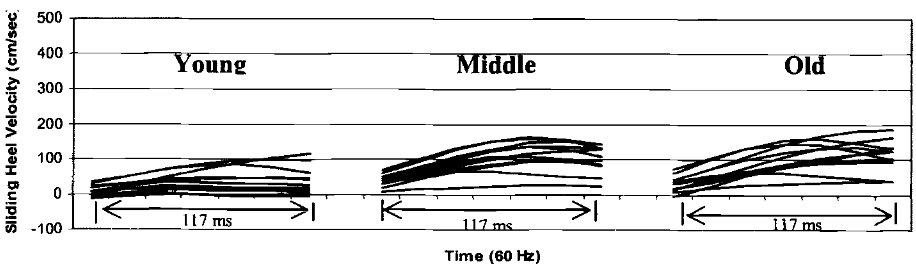

Figure 3 – Composite patterns of sliding heel velocity profile of each individual starting from heel contact to 117 ms after heel contact on the oily vinyl floor surface among young, middle, and old subjects.

The results of a one-way ANOVA on average sliding heel acceleration (H_{acc}) indicated significant difference in this parameter as a function of age group ($F_{(2,39)}$ $=5.448, p\approx 0.008$). Tukey-Kramer post-hoc tests indicated that the older-age group's H_{acc} was significantly faster ($p\approx 0.0001$) than younger age group. No statistically significant differences were found between the middle-age and older-age groups. (See Figure 4.)

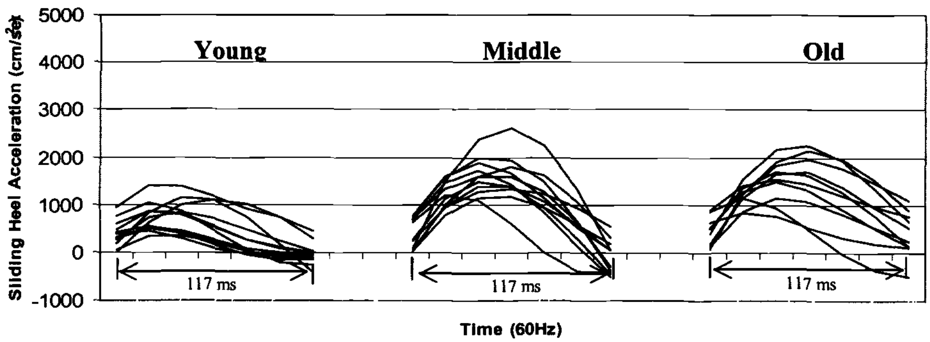

Figure 4- Composite patterns of sliding heel acceleration profiles starting from heel contact to 117 ms after heel contact on the oily vinyl floor surface among young, middle, and old subjects.

The results of a one-way ANOVA on adjusted friction utilization (AFU) indicated significant difference in this parameter as a function of age group ($F_{(2,39)} = 13.434, p\approx 0.0001$). Tukey-Kramer post-hoc tests indicated that the older-age group's AFU was significantly higher ($p\approx 0.001$) than younger-age group. No statistically significant differences were found between the middle-age and older-age groups.

The results of a one-way ANOVA analysis of RCOF indicated no statistically significant differences between the age groups ($F_{(2,39)} = 2.392, p\approx 0.11$). Figure 5 illustrates friction utilization (RCOF and AFU) as function of age groups.

The results of a two-way ANOVA on step length (SL) indicated a significant difference with respect to age group ($F_{(2,39)} = 4.735, p\approx 0.0144$). There were no statistically significant floor effects on SL ($F_{(2,39)} = 3.166, p\approx 0.053$). Tukey-Kramer post-hoc tests indicated that the middle age group's SL was significantly different ($p\approx 0.001$) from younger and older subjects. The older subjects step length was significantly shorter than the younger subjects. (See Figure 6).

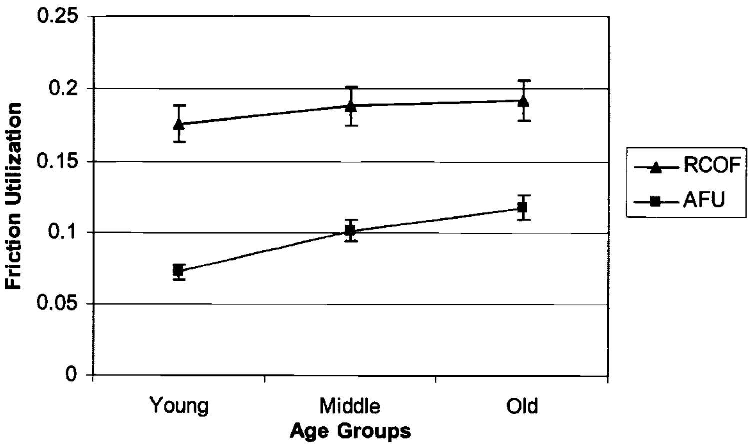

Figure 5 – Friction utilization coefficients (RCOF and AFU) among three age groups. RCOF was obtained on the (not-slippery) carpeted floor surface and AFU was obtained on the (slippery) oily-vinyl floor surface.

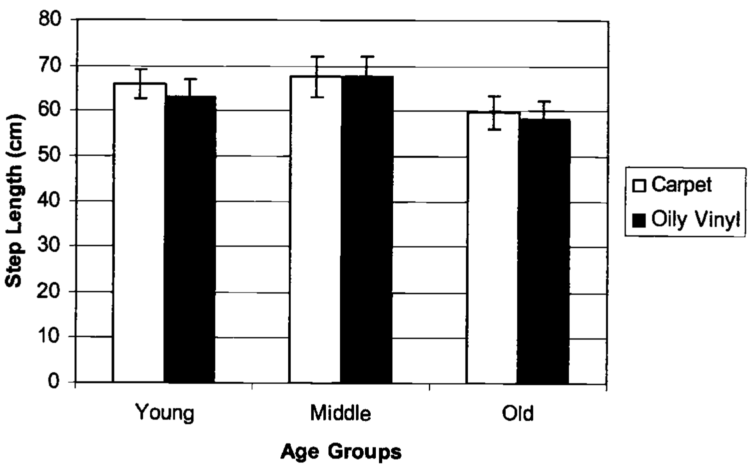

Figure 6- Step length of three age groups on the carpeted floor surface (not-slippery) and oily vinyl floor surface (slippery). Slippery floor surface was surreptitiously introduced to subjects.

The results of a two-way ANOVA on heel contact velocity (V_{hc}) indicated no statistically significant (p>0.05) horizontal heel contact velocity (V_{hc}) differences between the age groups ($F_{(2,39)} = 20885, p \approx 0.0678$). Additionally, there were no statistically significant (p>0.05) floor effects on V_{hc} ($F_{(2,39)} = 0.846, p \approx 0.437$). (See Figure 7.)

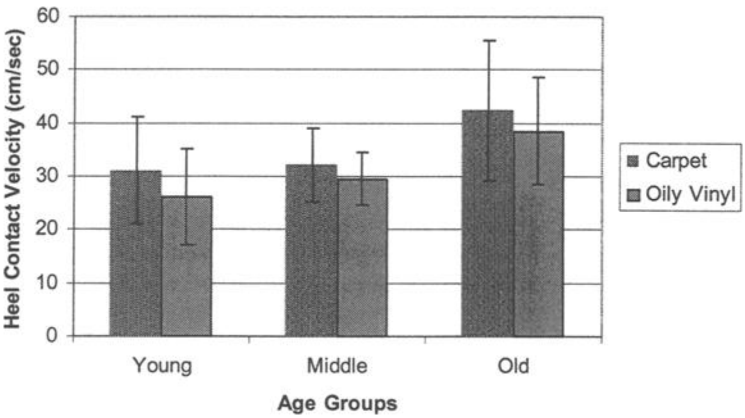

Figure 7- Heel contact velocity of three age groups on the carpeted floor surface (non-slippery) and oily vinyl floor surface (slippery). Slippery floor surface was inadvertently introduced to subjects. Heel contact was defined as the time when the vertical ground reaction force exceeded 10N.

Fall Frequency

A fall was identified if and only if two conditions were met:
1) when the sliding heel velocity was greater than the whole-body COM velocity (not reported here), and;
2) identifying a fall with visual inspection of the video recordings (i.e., subject's body clearly dropped towards the floor after slipping and was arrested by the harness before the impact).

The fall frequency results indicated that younger individuals in this study experienced 4 falls, middle-aged subjects experienced 8 falls, and older individuals experienced 12 falls.

Fall Recovery Threshold (FRT)

To provide information regarding the relationship between slip parameters and fall accidents, a fall recovery threshold was developed utilizing slip parameters aggregated by age group, collected from runs where a fall occurred. Bivariate correlations between each slip parameter and the number of falls were calculated across each age group to determine the strength of the association between the parameters and falls. Results indicated that when the subjects in each age group exceeded the fall-recovery-threshold limits, a fall resulted. Additionally, a stronger association was found between the number of falls and sliding heel acceleration than with either slip distance or sliding heel velocity.

Table 3 - Fall Recovery Threshold (FRT) across three age groups.

Variables	Young	Middle	Old	r^{2*}
Initial Slip Distance I (cm)	3.90	3.80	3.12	0.92
Sliding Heel Velocity (cm/s)	144.45	145.26	107.63	0.86
Sliding Heel Acceleration (cm/s^2)	1580.05	1310.52	1220.22	0.96

*Coefficient of determination between each slip parameter and frequency of falls.

Discussion

Epidemiological findings suggest that older adults experience severe fall-related injuries more frequently than their younger counterparts [14, 15]. Many possibilities for this difference have been proposed including both intrinsic (e.g., gait adaptation, musculoskeletal and sensory degradations) and extrinsic (e.g., medications and environments) factors, but with little agreement on actual mechanisms. It is not clear whether older adults experience severe fall-related injuries as a result of intrinsic factors associated with slip initiations (factors influencing friction demand such as gait adaptations) or due to uncompensated slips (factors influencing detection of and recovery from a slip). The aim of the current study was to provide better understanding of mechanisms involved in slip-and-fall accidents among different age groups.

Biomechanical analyses of human locomotion on slippery and non-slippery floor surfaces provided a method to assess slip severity among different age groups. We hypothesized that slip severity (as measured by slip distance, sliding heel velocity, sliding heel acceleration, and adjusted friction utilization) will be greater among older adults than their younger counterparts, resulting in more falls.

A method was developed to assess *slip severity* among different age groups. Utilizing three-dimensional coordinates of the heel and ground reaction forces, sliding motion of a foot on a slippery surface was characterized (i.e., distance, velocity, acceleration of the slipping foot, and friction demand). Specifically, slip distance was identified utilizing sliding heel velocity and acceleration profiles. Additionally, slip distance was further divided into SD_I and SD_{II}. SD_I was assessed to provide information concerning the severity of slip initiation and SD_{II} was assessed to provide information concerning the slip behavior after initiation of a slip. Furthermore, Peak Adjusted Friction Utilization (AFU) was calculated using ground reaction forces on the slippery floor surface to assess dynamic frictional requirements of the slipping foot.

In order to assess if test subjects had any awareness that the floor surface had been switched from carpet to the oiled tile, step length and heel contact velocity were analyzed for both floor surfaces. Previous experiment indicated that heel contact velocity and step length were significantly reduced when knowingly walking on slippery floor surfaces [16]. Lack of significant differences for these variables with respect to the floor surface suggests that subjects in current study were not aware of the floor-surface changes.

As indicated by several researchers, initial gait characteristics such as longer step length and higher heel contact velocity may adversely increase friction demand (RCOF) at the shoe/floor interface, increasing the slip potential [16, 17, 18]. Consistent with previous findings [16, 18], older adults step length was shorter than their younger counterparts. Although older adults' heel-contact velocity was on the average higher than the younger adults, this was not statistically significant. Furthermore, older adults friction demand (RCOF) was not significantly higher than their younger counterparts. These findings suggest that slip potential for older adults are similar to younger adults, and that younger as well as older adults are equally prone to slip initiation. This statement is further supported by the SD_I result on the slippery floor surface. No significant SD_I differences among age groups suggest that shortly after the heel contact (approximately 60-80 ms), younger adults as well as older adults slipped.

Lockhart [19] writes that older individuals were susceptible to falls more often than their younger counterparts. Consistent with previous findings, older adults experienced more falls than did the younger adults. Older adults slipped longer (SD_{II}) and faster than the younger age group. Furthermore, the middle-aged group exhibited slipping characteristics much like their older counterparts. Fall Recovery Threshold (FRT) measures suggest that sliding heel acceleration during slipping was a stronger fall predictor than sliding heel velocity. Furthermore, younger individuals FRT was higher on the average and suggests that the fall recovery threshold is not all same for the different age groups (i.e., younger subjects can slip longer and faster than older subjects and still recover from a slip-preventing a fall). Thus, in a given situation, older adults are at a higher risk for fall accidents. This result is further supported by higher AFU values for the older individuals. As indicated, younger individuals AFU (.074) was adjusted within the dynamic friction requirements (0.08). However, on the average, middle-aged (AFU = 0.10) and older individuals (AFU = 0.12) could not. Consequently, the result was longer slip distance (SD_{II}) and increased frequency of falls. Lockhart [19] wrote that the ability to successfully recover from a slip (thus preventing a fall) was affected by lower-extremity muscle strength, and sensory degradation among older adults. Thus, it seems that slip severity is dependent upon intrinsic changes associated with aging. Although implicated, further study investigating mechanisms involved in higher sliding speeds and slip compensation are needed.

Conclusions

1) All subjects slipped when confronted with the oily vinyl tile.
2) Older adults' friction demand (RCOF) and initial slip distance (SD_I) were not significantly different from their younger counterparts.
3) Older adults' slip potential at the time of the heel contact to shortly after the heel contact (i.e., slip initiation) are similar to the slip potential of younger adults, and that

younger as well as older adults are prone to the slip initiation. In other words, the characteristics of the slip initiation were very similar among the different age groups.

4) Differences of import occurred after slip initiation. Older adults slipped longer (greater SD_{II}) and faster than younger adults.
5) Fall-recovery-threshold (FRT) parameters indicated that younger adults were better able to recover from a slip (thus preventing a fall) with much higher sliding speed and longer slip distance suggesting that recovery thresholds (in terms of slip distance and sliding speeds) are not-at-all the same for the different age groups.
6) Older adults' were unable to lower their friction utilization on the slippery floor. If the utilized friction cannot be brought within the dynamic friction requirements, a fall is likely to occur.
7) We hypothesize that the inability to control slipping responses may be a result of the sensory degradation and muscle weakness.
8) Most of the current research on slips and falls concentrates predominantly on initiation of slips (i.e., RCOF), however, this study indicates that how slips result in a fall is important as well, especially for older adults.
9) Future research should focus not only upon the dynamics of slips, but upon the dynamics of falls.
10) It might be useful to explore shoe-bottom materials that have an increasing friction/velocity characteristic.

Acknowledgments

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In-Ju Kim[1] and Richard Smith[1]

A Critical Analysis of the Relationship Between Shoe-Heel Wear and Pedestrian/Walkway Slip Resistance

Reference: Kim, I. J. and Smith, R. M., "A Critical Analysis of the Relationship Between Shoe-Heel Wear and Pedestrian/Walkway Slip Resistance," *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424*, M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: This study seeks to clarify issues in pedestrian/walkway slip safety by exploring in detail the relationship between shoe-heel wear and slip resistance. Importantly, this paper addresses the fact that slip resistance changes as a result of wear-generated changes in the shoe-bottom and, to a lesser extent, the test surface. Insights from this paper may provide a better way of characterizing slip resistance than the commonly used averaged coefficient-of-friction (COF) value that would be compared against single-value pedestrian-friction safety thresholds. Specifically, we have derived an alternative, systematic slip resistance measurement methodology by observing the variation of COF with changes in the friction force as a function of interface wear between a shoe heel and floor surface under dry test conditions. Surface changes of both bodies were quantified using two extreme roughness parameters: R_{pm} and R_{vm}. It was found that massive wear occurred on the shoe-heel surface from very early stages of sliding and continued until the surface layer was heavily worn out. Heel contact conditions, such as initial strike time and position, changed significantly with wear evolution and, importantly, were directly related to the displacement of the friction force. Our results clearly showed that COF is not constant with respect to shoe-heel wear and, thus, friction is a function of a given set of materials as well as environmental and wear conditions.

Keywords: cof, dfc, friction, frictional force, slip resistance, surface alteration, wear

Introduction

The primary objective of this paper is to analyze critically the tribological characteristics of the frictional force generated between a shoe heel and a test-surface as a function of repetitive sliding wear.

[1] Research fellow and associate professor, respectively, School of Exercise and Sport Science, Faculty of Health Sciences, The University of Sydney, PO Box 170, Lidcombe, N.S.W., 2141, Australia.

Since slip-resistance measurements for the evaluation of pedestrian slip hazards began, a great deal of research has been undertaken and many different theories, devices and experiments have been developed to establish safety criteria in terms of static coefficient of friction (SFC) as well as dynamic coefficient of friction (DFC), in order to characterize the slip-resistance between the shoe and the floor. Presentlyre does not exist a single coefficient of friction (COF) value that can serve as a safety threshold for slip assessment. In fact, because each testing instrument has different systemic parameters and mechanical principles, it seems unreasonable to adopt a reference value without any reference to the instrument used for the slip-resistance measurements. This means that there is great debate about what constitutes a "safe" value for the COF between the footwear bottom and the underfoot surface.

Traditionally, friction is defined as the force that generates resistance to relative motion, developed between two bodies in contact with one another. More specifically, friction can be defined as the latent resistive force which opposes incipient movement at and parallel to the slip plane of two interfacing surfaces [1]. Normalization, that is, characteriation in terms of the the *relative* magnitude of this force, is done most conveniently by expressing it as the ratio of the force required to just overcome the resisting force to the force acting perpendicular to the two surfaces in contact. This ratio defines the COF.

Although the concept of friction is relatively simple, its measurement, analysis, and interpretation in the solution of real-world problems is quite a complex task [2-3]. One important aspect, which forms the focus of this paper, is that COF is not a constant. The value of the COF changes because friction measurements are inherently noisy and, importantly, because of friction changes over time as a function of wear of the interfacing materials [4]. In addition, friction phenomena observed at a sliding interface between the footwear and floor surface are diverse and combine various sub-mechanisms [4-6].

From a geometric point of view, almost all surfaces are rough on a microscopic scale and are comprised of an aggregation of micro- and macro-asperities [4]. The geometric characteristics of both shoe and floor surfaces are continually modified during sliding processes. That is, initial surface features and properties are significantly changed and modified—from the first moment of contact—by surface failures and wear evolution [4-8]. Thus, a single friction measurement for analyzing the multiple characteristics of the tribological phenomena between the footwear and the underfoot surface may not be 'good enough' to provide a true measure of the *intrinsic* slip resistance property between them. In spite of the importance of this matter, this issue has not been explored in depth.

In order to analyze how the geometry of a rough floor surface (one with randomly distributed asperites) interacts with the also rough surface of a shoe heel under load, it is necessary to study how the frictional force between the shoe and heel is generated. Since friction behavior is significantly related to surface topography, it is expected that the friction mechanism between the shoe heel and floor surface is accordingly affected by surface alterations and wear evolution during the relative movement between the shoe and the heel [4, 8]. While the COF during ambulation undoubtedly varies in a complex and non-uniform way, initial heel contact conditions have been found to progressively change with the wear evolution, and this result is directly connected with the modification of the friction-force component [7-8]. Thus, the COF is not a constant for any pair of the shoe-floor combinations sliding against each other under a given set of surface and environmental conditions.

For more complete characterization of the multi-dimensional characteristics of slip resistance between the footwear and underfoot surfaces, we believe that it is necessary to understand the tribological characteristics between the shoe and the underfoot surface as a function of the wear evolution between the surfaces. Because the wear that is generated at an unlubricated interface is greater than for a lubricated surface, characterization of shoe-bottom-floor friction as a function of wear evolution is especially important when the surfaces are dry. To perceive the fundamental aspects of friction and wear behaviors and mechanisms between the shoe and floor, to identify principal tribological characteristics between the two bodies, to eliminate the confounding effect of contaminants (other than those actually generated by the shoe bottom and/or floor), and because most shoe-bottom wear is generated while the interface is dry, our experimentation was limited to dry conditions. That is, our research was aimed at investigating intrinsic topographic variations and normal wear behaviors between the shoe and floor, without the confounding effects of lubrication. We acknowledge that lubricated floorings are potentially more slip hazardous than dry floors, as the traction mechanics and mechanisms between wet and dry surface conditions are fundamentally different.

Theoretical Background

Friction and wear phenomena are the results of extremely complex interactions between the surface and near-surface regions of two materials in contact. The physical, chemical, and mechanical properties in surface and near-surface regions may well differ from the corresponding bulk properties of the materials. Furthermore, these surface and near-surface properties can (and will) change radically as a result of interactions of the surface atoms with their environments and with each other. As a result, if it is necessary to know the COF of a particular pair of materials under a particular set of conditions, then the most reliable procedure would be to measure it experimentally, under conditions as close to the operating conditions as is feasible.

Hence, it must be considered that:

(1) the COF is not necessarily constant for any particular pairing of materials sliding against each other under a given set of surface and environmental conditions;
(2) the surface geometry can be quite complex and the characteristics of the mating surfaces can continuously change in the process of sliding; and
(3) the selection of test conditions for friction measurement will in fact influence the test results.

Strandberg and Lanshammar suggested that vertical force was one of the particularly important variables that slip resistance meters should reproduce based on tribological and practical experience [9]. Of many important parameters related to crucial gait phase, Redfern and Bidanda classified the vertical force, shoe heel velocity, and shoe contact angle as the most significant biomechanical parameters [10]. Wilson [11] and Grönqvist et al. [12] recommended that the range of vertical force in the testers vary from almost a whole body weight to 50% of body weight. In a recent study, Chaffin et al. [13] argued that although the basic assumption in computing the COF is that the friction force increases proportionally to the normal force holding the contacting surfaces together, under some circumstances this may not be true.

The effect of the normal load magnitude is not simple to predict. When a soft material such as crepe is loaded heavily on a rough surface, the deformation force effect on friction will be larger than when using a smooth surface or harder shoe material [13]. That is, an interaction between the shoe and floor surface exists that complicates generalities about COF under light and heavy loads. This fact is particularly troublesome for selecting a proper tester because some COF testing procedures use a very light normal load (less than 10 N), but others advocate a quite high load (about 1,000 N).

The angle at which the shoe heel first contacts the floor surface is an important factor in slipping. Hence, striking at a 'correct angle' would mean testing the most important part of the shoe in walking. A motor driven treadmill was built to investigate the human walking pattern and, importantly, the variation of the strike angle with walking speed as a function of the subject's height and gender [14]. The treadmill was designed to simulate walking on a flat surface, and up or down a ramp. Its speed was continuously controllable within the range of 0.3 to 2.2 m/s. A video system was used to record the walking pattern and the strike angle was measured off the TV screen in a playback-pause mode. 32 male subjects ranging from 1.55 m to 1.80 m height were tested. It was found that the strike angle varied with the walking speed, step size and subject's height. On a horizontal surface it lay within the range of 6 to 10° measured from the floor. Analyzing the distribution, a mean strike angle of 9° was chosen for the slip test.

Given that vertical, normal loads and strike angle are factors, it remains to select the test speed. As noted (Hoang et al. [14]), this would not be important where the COF is found not to vary significantly with speed. However, this need not be the case, as shown by Perkins and Wilson [15]. The need to include speed as a variable would add tremendously to the volume of tests to assess the relationship between shoe and floor materials. It would therefore be desirable to identify a speed which is representative of slipping risk and keep this constant during tests. At present, such a speed is still the subject of debate. Walking speed varies from 1 to 2 m/s but heel edge forward speed is likely to be considerably less than this just before strike. Strandberg [16] gives some experimental results for different subjects, in which this speed varied from 0.06 to 1.7 m/s. He also found the heel velocity at skid start varied from 0.08 to 0.32 m/s. After skid start, the shoe heel accelerated to a value above that of walking speed. He concluded that the speed of a dynamic test should be in the range of 0 to 0.5 m/s. Perkins and Wilson [15] concluded from similar measurements that "probably the ideal test speed would be 0.5 to 1.0 m/s, since the foot and shoe can be travelling at this speed when the heel tip contacts the ground. Even if slip starts from a static situation, such is the acceleration that the speed of slip is about 0.5 m/s after only 0.01 m slip distance." The commercially available Tortus floor friction tester uses a speed of 0.017 m/s. While this is low in comparison with the recommendations above, the developers argue that the effect of speed is not great for the floors tested [17]. On the other hand, the Sigler swinging pendulum tester has a test speed of about 2.7 m/s [18]. The dynamic friction tester used in this study was designed for an adjustable speed up to 0.6 m/s. In a preliminary series of tests, it was found that there was little variation of the results with speed (less than 8%) within the speed range of 0.2 to 0.6 m/s [19].

Experimental Method

Friction Test Arrangement

Fulfillment of our objective: the characterization of shoe-bottom/test-surface friction as a function of the wear evolution between the surfaces, requires the monitoring and analysis of:

(1) contact time and rate of increase of the friction force,
(2) heel-contact angle at the time of maximum friction demand, and
(3) surface roughness of the both shoe and floor surface.

A pendulum-type hydraulic friction test machine, shown in diagrammatic form (Figure 1) was used to measure the dynamic friction coefficient (DFC) between a shoe and a floor sample. This test machine consists of two hydraulic systems, a force component transducer (Kistler 3-Component Dynamometer, Type 9257A), an angular displacement transducer, and a desktop computer. This tester is constructed so as to simulate the movement and loading of the foot during heel-strike and initial-slip, and quantitatively determines slip requirement in terms of the DFC. The set-up parameters, e.g., heel contact angle, vertical load and its rate of increase, and sliding speed, are adjustable to match data taken from human subjects.

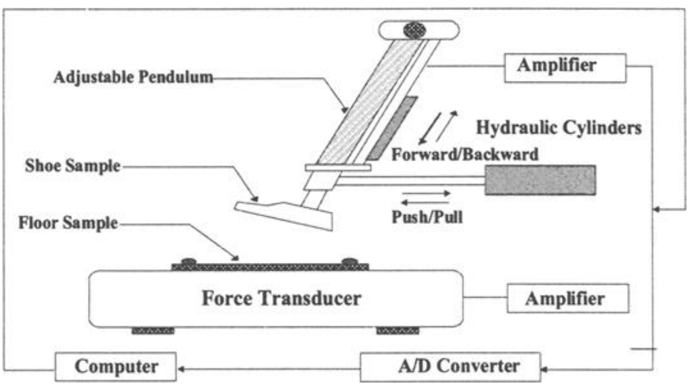


Figure 1 —*A diagram of the dynamic friction testing machine.*

The contact angle of the shoe can be adjusted by tapered shims between the shoe last and the base of the pendulum. This angle has proved to be a one of the most important variables in slipping [15]. The heelstrike angle we selected was based on a study using the force-measuring platform [15]. The vertical load was adjusted mainly by means of two nuts located near the upper end of the pendulum. The length of the pendulum was adjusted by these two nuts to change the vertical load applied to the floor sample. Some fine adjustments to the vertical load were also possible by a pressure control on the oil feed to the vertical hydraulic cylinder. The hydraulic system for the normal force in the friction tester provided a constant slipping velocity at up to 500 newtons (N) vertical load. The sliding speed was controlled by means of the flow control valve of the hydraulic unit, which controlled the flow rate of the hydraulic oil fed into the pushing cylinder. The speed of the test was measured by a rotary potentiometer driven by the pendulum shaft. The dynamic friction tester used for this study was designed for a speed of up to 0.6 m/s. In this machine, the whole shoe to be tested was mounted at the end of a pendulum mechanism. To minimize any movement, the shoe was nailed to the last. The floor surface specimen was glued to a steel plate that was bolted onto a force-component measuring instrument. In test, the shoe was driven forward by the horizontal hydraulic cylinder to contact the floor-sample surface at the heel edge. Another hydraulic cylinder mounted on the end of the pendulum simulated that part of the body weight supported by the leading foot at heel strike. As the shoe heel passed across the floor sample surface, the horizontal and vertical components of the resultant force were measured by the Kistler dynamometer upon which the floor sample was firmly mounted. This instrument gave two separate signals that were proportional to the friction (horizontal) and normal (vertical) force components respectively. The two hydraulic cylinders were in a common circuit supplied by a pump that was driven by an electric motor. The force component signals and potentiometer voltage during a test were recorded on a desktop computer that continually calculated the H/V force ratio..

Test speed. The dynamic friction tester used for this study was designed for an adjustable speed up to 0.6 m/s. In a preliminary series of tests by Hoang et al. [19], it was found that there were good results with speed variation (less than 8%) within the speed range 0.2 to 0.6 m/s. On the basis of Hoang et al.'s measurement results [14], the test speed for all tests was kept at a constant speed of 0.4 m/s.

Heel strike angle. A mean strike angle of 9°, based on the study of Hoang et al. [14], was chosen for the slip test. The contact angle of shoe heel can be adjusted by tapered shims between the shoe last and the vertical pendulum.

Body weight. An average body mass of 70 kg was presumed. The hydraulic system for the normal force in the friction tester can provide a constant slipping velocity at up to 500 newtons (N) vertical load [14]. Strandberg and Lanshammar found that the leading foot bears up to 60% of body weight, acting at the heel rear edge during heel contact [9]. Therefore, a maximum vertical component of the resultant force of 350 N was chosen and kept constant during the tests.

Test Specimens and Friction Tests

A PVC shoe was used for the friction test because of its tough and excellent slip resistance properties [5, 9]. For a flooring specimen, a smooth Perspex® (polymethyl methacrylate) plate, which was prepared by shot blasting to produce a roughened surface. The shoe was repetitively rubbed against the flooring specimen under clean and dry conditions. During the entire test period, the normal load and nominal contact area were kept constant. Measurements of slip resistance between the PVC shoe and Perspex sample were conducted 700 times and analyzed. Heel strike angle was also constantly investigated to observe its displacement against time as the function of rubbing cycles completed . During every rubbing cycle, the surfaces of both shoe and floor specimen were thoroughly cleaned with a fine brush to remove any loose wear particles. In order to observe the variations of the friction force, the dynamic friction results were divided into eight sub-groups (beginning with test Nos. 1, 15, 50, 80, 100, 300, 500 and 700) and monitored as a function of the contact sliding time

A laser scanning confocal microscope (LSCM) was used to measure the surface roughness of both bodies [4]. With this instrument, the surface roughness was measured three times on five different positions of each floor sample before and after the tests and then averaged. The profile ordinate data were read at 1 μm intervals for 200 evenly spaced data points over the assessment length of 200 μm. This information was used to calculate the surface roughness parameters, which are assumed to be representative of the test surface roughness in the sliding area. The geometry changes of the shoe and floor specimen were quantified by using two peak parameters – R_{pm} (maximum mean peak height) and R_{vm} (maximum mean depth) among a number of surface roughness parameters. During the initial period of sliding, we speculate that only a small number of the highest asperities of the floor surface will contribute to the friction between the shoe heel and floor surface. Hence, it would be useful to have a measure of the extremes of the departure of a surface profile. These extreme value parameters are sensitive indicators of high peaks and deep troughs in a surface. The most commonly used of these are the mean of maximum departures of the profile above and below the mean line, referred to as R_{pm} and R_{vm}, respectively [20].

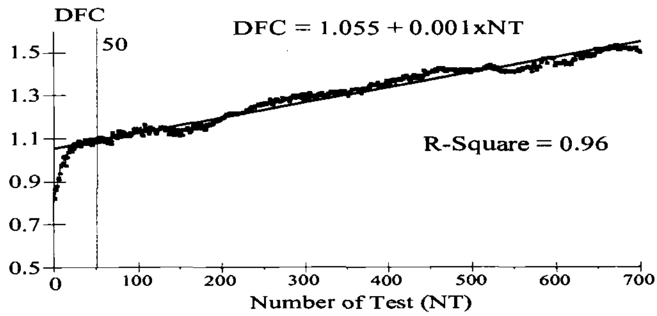
To identify wear debris and changes in the surface topography of each shoe and flooring specimen, three-dimensional images of both surfaces before and after the sliding were observed by a stereo scanning electron microscope (SEM). The SEM was operated at 10 kV setting to avoid radiation damages to the naked polymeric surfaces of each shoe heel and transferred polymer particles into the floors.

Overall Results

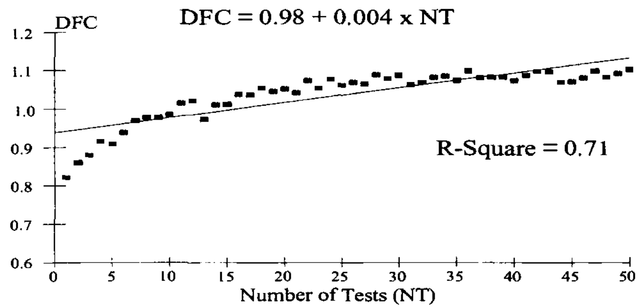
DFC Results and Wear Observations

Figure 2 plots the dynamic friction results between the PVC shoe and Perspex® floor surrogate. It shows that overall slip resistance gradually increased with sliding. In the very early stage of the friction measurements (until 50 times rubbing, see Figure 2 (b)) the DFC values increased more rapidly. This result seems to indicate that massive surface alterations and active wear were occurring at the sliding interface between the shoe heel and floor surface. That is, the outermost layers of the heel surface were extensively damaged by continuous abrasion. This aspect was easily observed by the naked eye and also confirmed by the observation of a large volume of wear particles from the shoe heel.

For the detailed investigations, the overall slip resistance results were grouped prior to analysis.



(a) Overall DFC results



(b) DFC results of the initial 50 times of sliding

Figure 2 — *Schematic plot of dynamic friction coefficients between a PVC shoe and a smooth Perspex flooring specimen under the dry conditions.*

With further sliding, the DFC gradually increased until around 460 repetitions and then stabilized. However, after 600 repetitions, the DFC slightly increased and then settled down. We believe that these DFC results are directly related with wear evolution between the shoe heel and flooring specimen. Because the shoe heel was a softer material, wear was concentrated on the shoe-heel surface. As the result, the geometry of the heel surface continuously changed due to abrasive and fatigue wear. At the same time, the surface topography of the flooring specimen had been modified through various mechanisms, such as material transfer, partial wear, and surface changes (Kim and Smith [4]).

The geometric features of surface alterations and wear evolution of the both materials were briefly identified by quantification of the two peak roughness parameters, R_{pm} and R_{vm}. Table 1 summarizes these two parameters for the shoe and Perspex® floor surrogate. After the tests, the roughness parameters for the two bodies showed clear changes. In the case of the PVC shoe bottom, the R_{pm} significantly increased (77.5 %) and R_{vm} significantly largely decreased (45.9 %). This demonstrates that plowing was a major wear mechanism in the increase of the both peak parameters. The change in these two roughness parameters clearly indicates that the worn surface of the PVC shoe heel constantly produced new, rougher surfaces by wear evolution. This seemed to reflect the overall slip resistance characteristics and explain a material property of the PVC shoe.

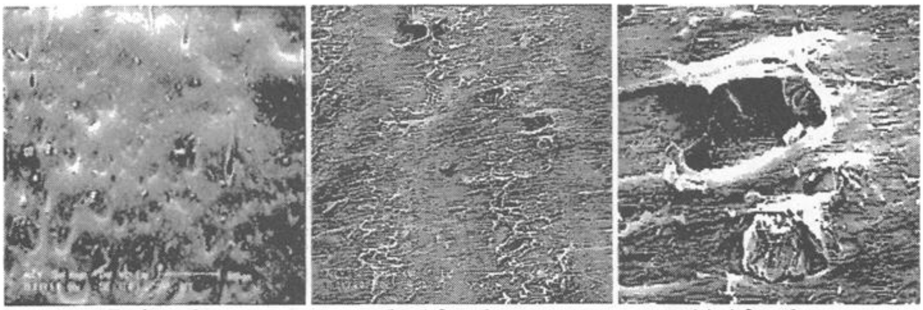
Table 1 — *Comparison of the two extreme roughness parameters of the PVC shoe and smooth Perspex specimen before and after the tests.*

Material	Test	Surface Parameters (μm)	
Type	Number	Rpm	Rvm
PVC	Initial	3.845	-5.145
Shoe	After 700	6.824	-2.783
Perspex	Initial	8.968	-9.483
Counterface	After 700	5.137	-3.396

In the case of the floor surrogate, however, R_{pm} and R_{vm} both decreased, by more than 40% and 60%, respectively. These figures clearly indicate that asperity heights of the Perspex surface were considerably modified by the tribological events. It should be pointed out that surface structural modifications of the flooring material occurred during the rubbing processes. If the actual areas of contact between two mating surfaces were initially formed at the highest asperities of the mating materials, these highest asperities at the time of initial contact would play a vital role in inter-surface adhesive bonding. This characteristic variation of the surface topography could be best represented by R_{pm}. According to this mechanism, a reduction in R_{pm} would produce a corresponding reduction in the adhesive force between the two mating bodies and thus affect the slip resistance results. If the slip resistance tests had proceeded further, it would be most likely that the topography of the Perspex® surface would become smoother and/or the surface asperities would become less sharp. From this aspect, the R_{pm} seemed to show the greatest relative changes from the initial to the rubbed state.

The change rate of the R_{vm} parameter showed a higher level of change than R_{pm}. This result supports the assumption that the fragments of polymeric particles from the shoe heel were embedded into the valley areas of the Perspex® floor surrogate. If this had been the case, it could create a more uniform film of the deposited material in all the surfaces and thus explain the more uniform DFC measures obtained at the later stage. In this experiment, the change in the profile asperity depth, therefore, was one of the major causes of the reduction of surface roughness. Hence, the two peak parameters seem to be important variables for detecting friction and wear processes of the shoe and the floor.

In order to examine the initial surface status and surface changes and wear evolution, three-dimensional images were obtained from the initial surfaces as well as the worn surfaces of the shoe heel and floor specimen. Figures 3 and 4 show micrographs from the PVC shoe heel and Perspex® flooring specimen, respectively. In the case of the PVC shoe, the initial heel surface showed shiny and smooth porous smooth asperities without any specific tread shapes (see Figure 3 (a)). After sliding, the initial smooth and porous surfaces of the PVC shoe heel were broken open and formed cavities on its surface layer, creating a new rough surface (see Figures 3 (b) and (c)). This result might substantially contribute to increase of the surface roughness to the real contact level achieved by penetration of the hard asperities of the floor surrogate. This surface roughening seemed to significantly contribute to the increase in the DFCs as shown in Figure 2. This aspect was also confirmed by the measurements of the two extreme roughness parameters, R_{pm} and R_{vm}.



(a) Before the test (b) After the test (c) After the test

Figure 3 — *Micrographs of the PVS shoe: (a) Initial heel pattern (b) Lens magnification x150 (c) Lens magnification x200.*

(a) Before the test (b) After the test (c) After the test

Figure 4 — *Micrographs of the Perspex® flooring specimen: (a) unworn surface (b) Lens magnification x2000 (c) Lens magnification x2000.*

Figure 4 shows the micrographs of the Perspex® surface before and after the test. The examination of the micrographs reveals that the initial surface was covered with a number of small indented asperities caused by the blasting technique for roughing the surface (see Figure 4 (a)). As assumed, the rubbed Perspex® surface resulted in significant surface modifications (see Figure 4 (b) and (c)). The micrographs clearly showed that repetitive sliding resulted in the massive transfer of polymer particles from the shoe heel to the Perspex® surface. The transfer occurred in the form of small fragments, irregular shapes of polymer particles, that filled the asperity crevices in a number of locations and that were also scattered the surface.. The effect of the latter would be a cause of slight increase in the roughness of the Perspex® surface along the sliding direction. In the case of the former, the deposition of polymer fragments would fill the valleys, even causing accumulation over the surface in discrete locations. The Perspex® surface itself was also damaged by the friction tests. The fresh parts of initial surface were heavily cracked after the sliding so that large particles of polymer debris were able to embed themselves into the cleaved surface. Thus, further sliding damage under the steady-state wear regime was most likely a function of both the polymer debris deposited on the Perspex® surface and of shoe-heel wear.

Friction Force and Heel Strike Angle

Friction Force. Figure 5 shows the displacements of the friction force as a function of the test-cycle number. The overall results were plotted against eight different time intervals of sliding – 1, 15, 50, 80, 100, 300, 500, and 700, respectively. These results were further aggregated into two groups–below 100 sliding cycles versus over 100 cycles for summary analysis. This division was accomplished to observe major trends of the variations of friction force against the number of sliding cycles (see Table 2). The changes of friction force showed similar pattern after 100 times of sliding.

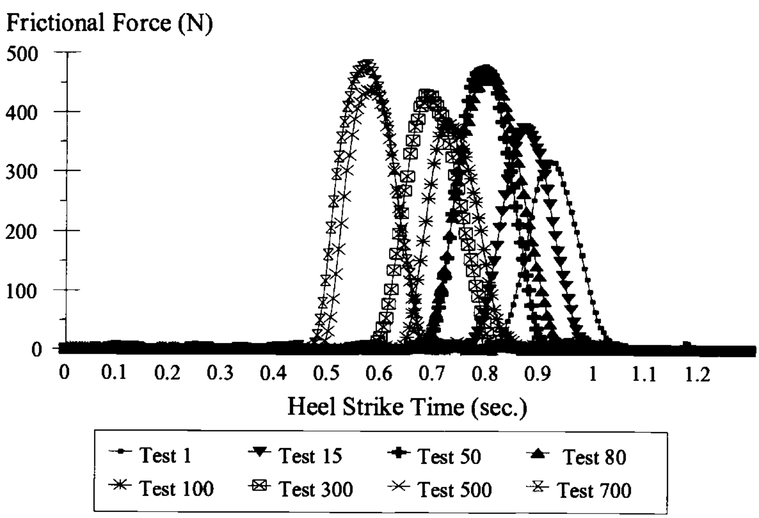


Figure 5 — *Schematic plot of the changes of the friction force components against a heel contact time interval as the function of test numbers.*

From Figure 5, we made the following observations:

(1) Initially, heel strike occurred at 0.8 second.
(2) After the 50 slides, heel-strike occurred at 0.7 second At this time, the friction force reached its next-to-highest point (474 N) and the DFC value also significantly increased (see Table 2).
(3) Between 50 and 80 slides, there were no significant changes in the friction force or heel strike time.
(4) After 80 slides, the friction force was significantly reduced (from 464 N to 376 N) and the heel strike occurred 0.05 sec earlier (see Table 2).
(5) At 100, the friction force and the DFC showed almost identical values compared with the 15 slides even though the heel strike was earlier (by over 0.1 second) (see the shaded areas in Table 2).
(6) After 100 slides, the friction force gradually increased and the DFC value also increased. This increase continued until the end of the test. The heel strike time between the 100 and 300 times of sliding occurred 0.1 second earlier at 0.6 second.
(7) After 300 slides, the friction force did not increase, but the DFC value increased slightly and the heel strike occurred 0.5 second earlier.
(8) After 500 slides, the friction force and DFC value increased slightly, reaching their maximum values. (see the dotted area in Table 2). The heel strike occurred marginally earlier, occurring at 0.48 second.

Table 2 — *Comparison of the DFC values and friction forces between the PVC shoe bottom and Perspex® floor-surface surrogate during the slip resistance tests.*

Test Group	Test Number	DFC	Friction Force (N)
Group I	1	0.821	284.9
	15	1.069	375.4
	50	1.344	473.8
	80	1.341	463.6
Group II	100	1.063	375.9
	300	1.215	429.0
	500	1.296	448.3
	700	1.395	492.9

After the sliding tests were completed, it was found that the heel strike times were significantly reduced (over 40%) from the initial 0.8 second to the final 0.48 second. We hypothesize this seems to be directly related to the growth of the heel contact area. That is, the first part of the heel area to contact the floor specimen progressed towards the front of the shoe as the sliding wear evolved and reduced the contact time from the backward swing phase of the pendulum arm. See Figure 6. Surface changes of the shoe heel were clearly observed at the end of the test. In this process, the wear increased the size of the contact area from the initial heel contact size.

Heel Strike Angle. Figure 7 shows the overall changes of the heel strike angle during the test. In this figure, following important aspects were found.

(1) The initial heel strike angle was very unstable. At first contact, three random spikes were observed at 0.27, 0.48, and 0.75 second respectively. These spikes seemed to be

caused by the initial wear evolution between the PVC shoe heel and Perspex® test surface. That is, the heel surface experienced a localized pressure caused by initial contact and would be consistent with geometric peel-off caused by sliding as observed in a previous study [8]. During this process, there could be a trend towards geometrical mating and comparative matching between two surfaces. Hence, the heel strike angle displacement became unsettled.

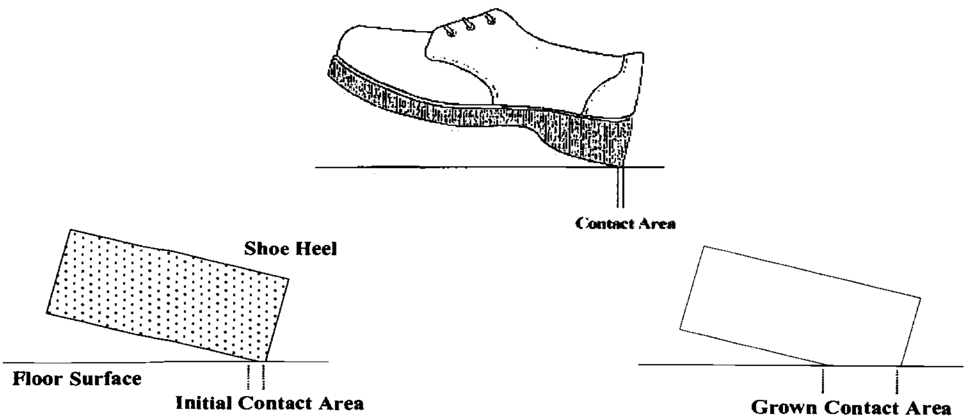


Figure 6 — *Schematic illustration of the variation of contact area between a PVC shoe and a smooth Perspex® floor surrogate.*

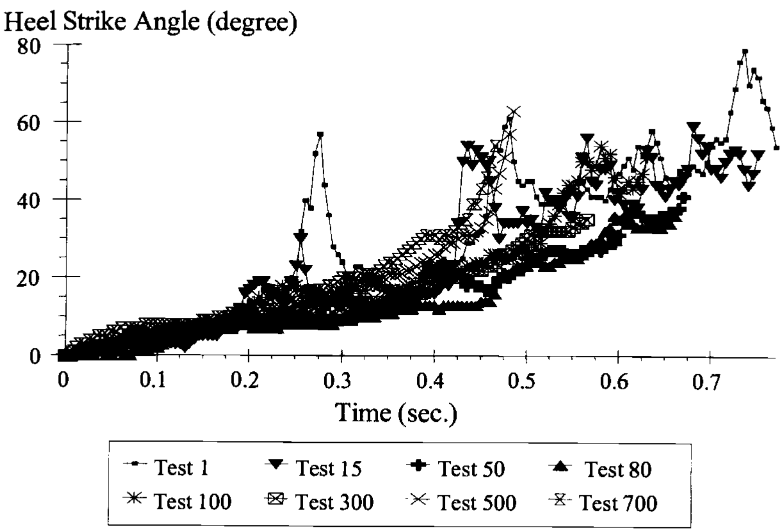


Figure 7 — *Schematic plot of the changes of the heel strike angle against a time interval as the function of test numbers.*surface.

(2) With the further sliding, the heel contact was stabilized and striking time was also shortened. That is, progressive wear between two surfaces gradually changed the

surface conditions so that the contact area became wider and smoother. This means that heel contact time was shortened and a high level of matching between two surfaces was attained.

(3) The heel toe-off time was also shortened with the continuous sliding so that the slope of each heel-strike angle became higher.

The above results clearly demonstrated the changes of the friction force with repetitive sliding even though all the experimental conditions such as the shoe, floor specimen, and vertical load were kept constant. From these results, the following important inferences can be made:

(1) The initial sliding period (up to 50 repetitions) is extremely significant in the slip-resistance evolution between the shoe and floor specimen. During this stage, almost all the major tribological characteristics: wear, surface alterations, and geometric interactions seemed to occur at the surfaces of the both shoe bottom and floor surrogate. Thus, the wear history in any test should be considered carefully when slip resistance measurements are conducted and reported. Because surface structures of any used or tested shoe and floor may well be significantly different compared with similar items in new condition, it is important to conduct tribometric tests with the condition of the test foot and test surface in specified and repeatable condition.
(2) Change of friction force as a function of wear should be considered to ensure the reliability of slip resistance measurements because wear can directly effect the DFC results.
(3) Initial heel-strike time becomes shorter, probably due to increase of the contact area between them.
(4) Initial heel strike angle gradually increases as a function of wear.
(5) The surface topographies of both shoe and floor specimens are significantly changed by wear so that wear characterization of the sliding interfaces between the shoe and floor surface may need to be analyzed and/or standardized for certain any friction-measurement situations.

Conclusions

This study explored the tribological characteristics of the friction force caused by surface changes and wear evolution that took place at the sliding interface between a PVC shoe and a smooth Perspex® floor surrogate. Sliding friction wear significantly changed the surface of both the shoe bottom and the floor surrogate, with consequent effects on the friction force. Results from the two peak roughness parameters showed that significant changes took place on the surface areas of both bodies. Furthermore, it was found from the microscopic observations that the progressive wear was more severe than expected and, importantly, initiated in the very early stages of sliding. During the wear process, the friction force was greatly influenced by the sliding between the two materials although all the initial experimental conditions were kept constant. This fact clearly indicates that DCF can vary as a function of wear evolution for some shoe-floor combinations. That is, slip resistance property depends not just on the friction when a slip starts, but on how the friction varies as a slip progresses. Therefore, single-threshold friction comparisons may be insufficient to describe the slip resistance behaviour between a walkway surface and a shoe heel or sole [21]. Furthermore, friction is very sensitive to the state of mating surfaces that are in contact. This implies, at minimum, that is very important in walkway-safety tribometry to bring the test foot and test surface into a 'standard state' before testing [22]. In this context, this paper discussed fundamental issues on the characterisation of the friction coefficient and addresses issues in the interpretation of COF index, including its consistently changing aspect during the evolution of wear-related material changes. Factoring in wear-related material changes, as explored in this study, may provide a way of improving the reliability of walkway-safety friction determinations over the older averaged-COF-value methodology, and make progress towards accounting for one of the mechanisms underlying COF variability.

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WALKWAY-SAFETY TRIBOMETRY

H. Medoff,[1] *R. Brungraber,*[2] *C. Hilferty,*[1] *J. Patel,*[3] *and K. Mehta*[1]

Variable Inclinable Stepmeter: Using Test Subjects to Evaluate Walkway Surface/Footwear Combinations

Reference: Medoff, H., Brungraber, R., Hilferty, C., Patel, J., and Mehta, K.,"**Variable Inclinable Stepmeter: Using Test Subjects to Evaluate Walkway Surface/Footwear Combinations,**" *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424,* M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002

Abstract: A variety of techniques have been used to measure walkway-surface/shoe-outsole slip resistance, employing both stationary and portable devices. In operation, typically, a shoe outsole material is placed in contact with a walkway surface and the ratio of the tangential force to the normal force at motion inception is a measure of the static coefficient of friction between the surfaces.

Recently introduced in Europe is a motorized inclinable ramp. A test subject walks both up and down the inclineable ramp and the ramp angle is incrementally increased until a slip occurs. The tangent of the ramp angle when slip occurs is an indication of the slip resistance between the walkway and shoe bottom. The ramp surface can be covered with a liquid for testing wet floor surfaces

The device described in this paper, called a 'Stepmeter,' is a simplified ramp device. It has a test subject stepping down with one foot on a variably inclinable ramp surface. The test subject's other foot rests on a flat, level surface. The ramp angle is incrementally increased until the subject's foot slips. The tangent of the angle at slip is a measure of the slip resistance between the shoe bottom and walkway surface. Tribometer test feet were constructed from the same shoe outsoles as on the shoes worn by the test subjects. These test feet were used in two portable tribometers on the same test surfaces as used in the device we developed.

Preliminary results indicate that this device can reproduce consistent results. Stepmeter results and the (limited) portable-tribometer slip resistance test results were similar.

Keywords: slip resistance, Stepmeter, DIN Ramp, tribometer

[1] Associate Professor of Engineering, Penn State University, 1600 Woodland Road, Abington, PA.
[2] Slip-Test Inc., Spring Lake, NJ.
[3] Penn State University, 1600 Woodland Road, Abington, PA.

Introduction

In measuring walkway-surface/shoe-outsole slip resistance, a variety of techniques have for many years been used. These have included both laboratory-only devices, e.g., the James Tribometer, and field-measurement capable devices, e.g., Horizontal-Pull Slip Meter, Portable Articulated Strut Tester (PAST), and Portable Inclinable Articulated Strut Tester (PIAST). Each of these devices has its own advantages and disadvantages, its own adherents and critics [1,2,3,4].

Recently [5], a motorized inclinable ramp, using test subjects walking both up and down the walkway surface, was introduced and has been adopted in Germany (DIN Standard 51130). This standard is "used as a qualification test to determine and evaluate the slip resistance of floor coverings intended for use in work room[s] and area[s] with an increased risk of slipping." The 'contaminant' used on the walking surface is engine oil (SAE 10W-30), spread over the test surface evenly with a paintbrush. Three standard floor coverings are used in an initial test procedure for calibration of the test subjects. These floor coverings have had their acceptance angles predetermined (within a 95% confidence interval). The test subjects walk facing down the ramp, wearing a safety harness, taking steps half a shoe length forward and back over the test surface, while the angle of the test surface is incrementally increased at one degree per second. This test is repeated three times (always starting from the horizontal) on each of the standard floor coverings. After each slip, the test stops, and the ramp angle is measured. RAPRA Technology Limited [6] uses a variation of the German DIN ramp to test coefficient of friction between shoes and flooring materials. Their method uses outsoles without pattern made of a specific rubber compound and a prescribed surface finish. SATRA [7] uses another type of ramp test, with the operator walking up and then down a ramp while a co-worker records the severity of slip: slight, moderate and uncontrollable. Reportedly, interpretation of results is problematic.

Slow motion photography and force plate studies [8] have shown that, for 'normal' walking, parallel-to-the-surface movement of the foot ceases just before heel contact. In order for slip to occur, one must first start to slip, i.e., overcome the static coefficient of friction (SCOF). Some pedestrians, e.g. children scuffing their heels as they walk, may have parallel-to-the-suface movement of the foot at heel contact so that the dynamic coefficient of friction (DCOF) would control the initiation of slip. For most walkers, however, the DCOF would only be of interest in predicting whether or not a slip, if it occurs, could be controlled.

In the presence of water or other liquid contaminants, slip-resistance is certainly a valid concept. The hydrodynamic genesis of slip resistance under wet conditions must not be confounded with not-analogous dry-surface friction mechanisms.

The usual dry-surface model used to characterize friction is a weight (W) developing normal and surface-contact forces (F_S and/or F_D) between the two surfaces. F_S is the magnitude of force needed to initiate motion of the weight; F_D is the magnitude of the surface force needed to continue motion of the weight, W. The surface forces are measured by a dynamometer. The SCOF is F_S/W and the DCOF is F_D/W. This is a valid model for considering the dry-surface friction if the surfaces are non-resilient, but lacking as a method used to measure friction *vis à vis* pedestrian safety. In addition to the problems of introducing extraneous acceleration-generated forces, as well as possible error due to misalignment of the friction force, there is a more serious issue when testing wet surfaces. Any time delay, however brief, between the application of the normal (or contact) force (W) and the application of the parallel-to-the-surface friction force (F) may cause the contaminant be squeezed out to a thin layer between the contacting forces which may mitigate or eliminate the hydrodynamic effects that form the phenomenological basis of wet-surface pedestrian slip resistance. Such wet-surface test results, particularly on smooth, hard floors, may anomalously show an improved slip-resistance compared to the same surfaces under dry condition, clearly at variance with common experience.

To yield test results that are representative of walking on wet floors, the device measuring slip-resistance must apply the normal and friction forces simultaneously, as occurs during walking. If the friction force is applied first, dynamic friction is measured, and if the normal force is applied first, the hydrodynamic effects will be mitigated or eliminated, resulting in unrealistically high friction values. The tribometers used in the present study (the PIAST and VIT) apply the normal and tangential forces simultaneously; they have been found to yield reasonable values of slip-resistance under wet and dry conditions. Under dry conditions they can measure the SCOF.

The Stepmeter described in this paper is a type of ramp. The test subject does not walk upon the ramp but, rather, steps down with the shod foot on the variably inclined ramp surface (see Fig. 1). The angle of this ramp is controlled by a hydraulically operated piston, which through the design of the mechanism, allows the ramp angle to be varied incrementally. The test subject always has one foot on a flat, stable surface, with the other foot repeatedly contacting the angled ramp surface. The subject's hands, for safety, are placed slightly above the Stepmeter's handrails. In addition, the subject wears a safety harness.

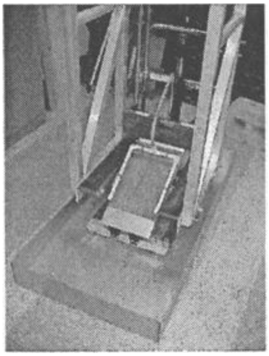


Figure 1–*The Stepmeter and frame.*

The entire device sits in a basin containing a liquid (typically water, but oils can also be used). A pump and piping system allows this liquid to be circulated over the angled ramp surface, thus allowing for testing under wet conditions. At each new ramp angle, the test subject 'steps down' onto the ramp surface, taking care not to impart any forward momentum of their foot relative to the walkway surface. The process continues until a discernible slip occurs, at which time the test stops, and the ramp angle is recorded. The tangent of the ramp angle (at slip) is the Stepmeter 'equivalent' of the acceptance angle of the motorized DIN ramp, or the Stepmeter 'equivalent' of the slip-resistance reading of a PIAST or VIT.

Both the DIN Ramp and the Stepmeter require the use of a test subject wearing a test shoe (or shoes) in order to evaluate a test surface. The DIN ramp requires the test subject to walk both forward and backward down (or up) the floor covering being tested, and the test procedure allows for the calibration of the floor covering and test subjects. Thus, the DIN Ramp incorporates the angle of stride and the ramp inclination angle, and when a slip occurs, the tangent of the acceptance angle of the DIN Ramp is not comparable to the measured coefficient of friction obtained from an appropriate tribometer. Therefore the DIN Ramp acceptance angle is not readily comparable to tribometer results. The angle of the test surface on the Stepmeter, when slip has occurred, is directly comparable to the slip resistance obtained by an appropriate tribometer. The safety harness used on the DIN Ramp, due to the motion of the test subject, may interfere more with a subject's behavior than the safety harness used on the Stepmeter.

Testing was performed to validate the following hypotheses:

Hypothesis I: Wet polished granite will provide a lower slip resistance than wet unglazed ceramic tile.

Hypothesis II: Different shoe outsole patterns will result in different slip resistance values on the same walkway surface.

Hypothesis III: The Stepmeter and typical tribometers give similar results.

Materials and Methods

A commercially available hydraulic lift-jack was used to elevate the ramp surface. The forks of the jack (4.5" wide by 24" long) were modified to allow support for the walkway surface being evaluated, located between the forks, to pivot, thereby changing the ramp surface angle as the forks were raised. This plate could accommodate walkway surfaces up to twelve (12) inches wide by twenty four (24) inches long. In the testing described, a twelve inch square test section was used. Plastic tubes (with a series of holes in their sides) were attached adjacent to each side of the walkway surface. A pump, moving the contaminant through the tubes, bathed the test area in a continuous layer of liquid. An aluminum safety frame (composed of 2" square tubing) was attached to the external sides of the forks. An integral handrail (2" diameter aluminum tubing) was incorporated into this external frame.

A total of ten healthy male test subjects with no history of foot problems were used. All had a shoe size of approximately $10^1/_2$. The test subjects were instructed to rhythmically step on the test surface with a repeatable, consistent pattern. They were instructed to not impart any forward momentum to their test foot, just step up and down. The test subject, wearing the safety harness, stepped down with the test foot onto the ramp surface at each new angle. Subjects were instructed to not use the supplied handrails, but keep their hands slightly above them.

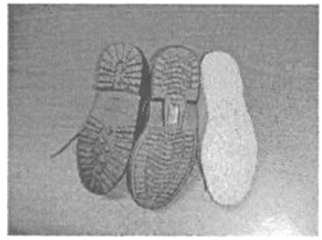
The inclination of the test surface was increased in increments of approximately five degrees, measured with an inclinometer reading to the nearest $^1/_2$•, with the test subject stepping down onto the test surface at each angle. This was repeated three

times for each angle. If the subject did not slip, the forks were raised and the process repeated until a slip occurs. After slip occurred, the process was repeated twice again. Thus, the angle of slip for each combination of test subject, shoe, and walkway surface was tested three separate times.

Three pairs of shoes were tested (See figure 2.); one of each pair on the Stepmeter and its mate was used for tribometer specimens. Tribometer testing was performed as per manufacturer's instructions and ASTM standards.

Figure 2–*Shoes used in the testing*

(Left to right)
(1) Route 66
(2) E-Z Strider
(3) Boat shoe



Two test surfaces were used: unglazed ceramic tile and polished granite. (See figure 3.)

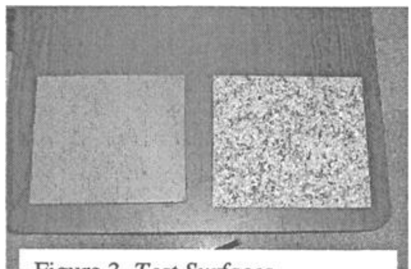


Figure 3–*Test Surfaces*
(left) Unglazed Ceramic Tile
(right) Polished Granite

Results

For each of the two flooring materials, three observations of slip resistance for each of the three shoes were taken, a total of 2x3x3x10 = 180 slip tests over the ten subjects. The following table displays the mean slip resistance values.

Table 1-Summary of Results

	Wet Polished Granite			**Wet Unglazed Ceramic Tile**		
Subject	**Shoe 1**	**Shoe 2**	**Shoe 3**	**Shoe 1**	**Shoe 2**	**Shoe 3**
1	0.281	0.411	0.307	0.617	0.582	0.791
2	0.338	0.319	0.306	0.547	0.666	0.88
3	0.287	0.456	0.325	0.65	0.65	0.74
4	0.274	0.338	0.293	0.569	0.692	0.8
5	0.277	0.371	0.377	0.597	0.581	0.781
6	0.271	0.397	0.452	0.495	0.577	0.679
7	0.348	0.499	0.543	0.613	0.625	0.718
8	0.287	0.394	0.477	0.543	0.593	0.772
9	0.287	0.411	0.414	0.525	0.578	0.781
10	0.287	0.424	0.532	0.618	0.601	0.81
Average	*0.294*	*0.402*	*0.403*	*0.577*	*0.615*	*0.775*
Adjusted Average	*0.290*	*0.386*	*0.357*	*0.578*	*0.620*	*0.792*
St. Dev.	*0.0267*	*0.0527*	*0.0959*.	*0.0492*	*0.0394*	*0.0546*

A screening Analysis of Variance was done using JMP, a common statistical program, with the SCOF as the dependant variable, and Subject, Surface, and Shoe as factors. All were significant ($p < 0.02$ for Subject, and $p < 0.001$ for Surface and Shoe).

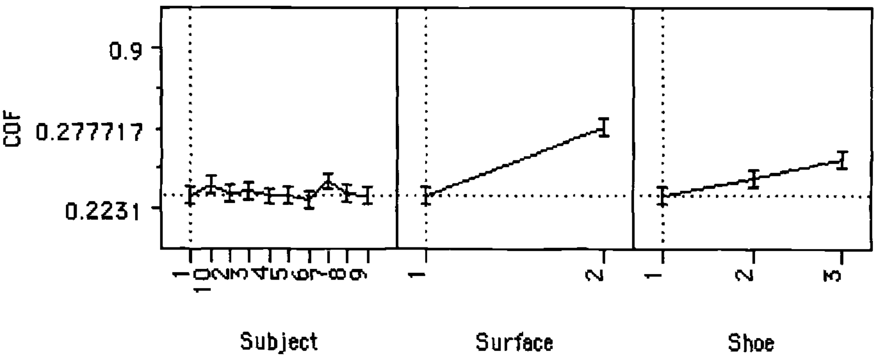


Figure 4–*The results of the screening ANOVA.*

When the individual Subject effects were examined, only Subjects 6, 7, and 10 were significantly different from the group. In a manner analogous to that of the DIN ramp tests, where 'not-standard' pedestrians are eliminated from the test program, the averages of all but subjects 6,7, and 10 were calculated and given in the table row entitled "Adjusted Average." The graph below summarizes the averages, adjusted averages, and tribometer results by shoe and surface.

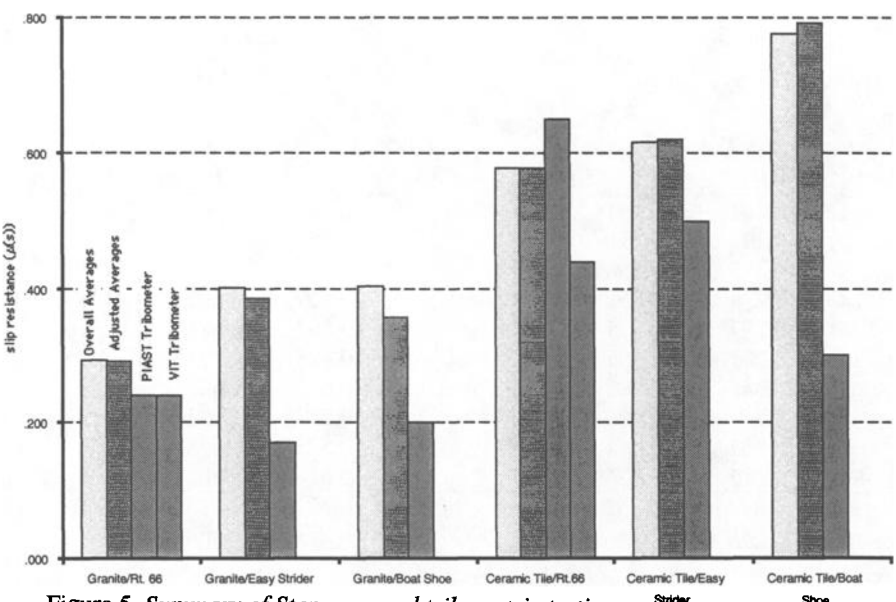


Figure 5–*Summary of Stepramp and tribometric testing.*

The three hypotheses that we postulated were at least provisionally confirmed:

I- These data are consistent with our hypothesis that the wet unglazed tile surface will have a higher slip resistance than the wet polished granite surface.

II- Least-squares ANOVA indicated that the Surface_Shoe interaction was significant ($F(2,54) = 9.75$), implying that the shoes act differently on the different surfaces. Specifically, it was clear that the Boat Shoe was significantly more slip resistant on the ceramic tile than the other shoes, but did not behave differently than the other shoes on the Granite.

III- The data shows that for the tested tribometers, results were similar to the Stepmeter results, or conservative, i.e., lower.

Conclusions

A device has been developed that can measure the slip resistance of shoes being worn by test subjects on walkway surfaces in the presence of contaminants. The slips experienced by the test subjects did not result in any injuries, and the safety harness operated appropriately. The test subjects did not report any difficulty in repeating the "up and down" motion required for the test. The reliability of the data (ten subjects, three shoes, two test surfaces, three trials each) was found to be adequate. The results showed that the device could discriminate between floor surfaces (with the same shoe being worn), and or shoes (on the same floor surface). There was an interaction between floor surface and shoe. The results were roughly comparable to those obtained from tribometers under the same conditions.

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Hisao Nagata[1]

An Analysis of the Sliding Properties of Worker's Footwear and Clothing on Roof Surfaces

Reference: **Nagata, H.**, "An Analysis of the Sliding Properties of Worker's Footwear and Clothing on Roof Surfaces," ***Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424*, M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.**

Abstract: To obtain information needed to prevent falls from the pitched roofs of wooden houses, the slide characteristics of roofing materials were evaluated using a clothed dummy and various footwear on an experimental, adjustable pitched roof. To determine sliding properties of worker's clothing and footwear, five roofing materials, viz., sheet metal, ceramic tile, slate shingle, bitumen felt, and plywood were tested. Slide characteristics of three types of footwear: sneakers, safety shoes and Japanese construction worker's footwear were tested. The most slippery roofing was sheet metal in wet conditions. Sheet metal and plywood roofing surfaces showed remarkably large reductions in the sliding-friction coefficient when they became wet. Thus, should it rain while working on a roof, the unexpected reduction of friction can trigger roof-fall accidents, especially on sheet-metal and plywood surfaces. The frictional properties of clothing on sheet metal and plywood in dry conditions are much lower than that of footwear. That implies that there is a great possibility of sliding down even a gently-pitched roof in dry conditions if a worker's body weight cannot be supported at the shoe soles, typically because of a loss of balance.

Keywords: slip and fall, roof safety, roof, footwear, roofing material, slip resistance

Introduction

A large number of occupational accidents are caused by falls occurring in the construction industry. According to 1999 statistics on occupational mishaps in Japan [1], 41% of fatal construction-industry accidents were caused by falls from roofs, scaffolds, ladders, eaves, girders, etc., and the percentage of such fatal accidents is mounting year by year. The wooden-building construction sector has more accidents than other related sectors [1]. Work-related falls from roofs remain a significant problem for workers in construction industry [2]. This paper discusses research and analysis of slide characteristics on roofs aimed at preventing accidents caused by falls from roofs. It focuses not only on assessing the slip factors leading to falls from roofs under both fair and rainy weather conditions, but also explores the sliding-resistance properties of

[1] Head of Research Division of Construction Safety, National Institute of Industrial Safety, 1-4-6 Umezono, Kiyose, Tokyo 204-0024, Japan.

footwear used on roofs. This paper analyses only sliding down roofs, and not rolling or tumbling off a roof.

Background

The measurement of kinetic friction is, in many ways, more straightforward than the measurement of static friction, as the measurement of static friction by an inclined plane presents more of a reproducibility problem. Measurements of friction of rubber and plastics in shoes are influenced by many factors, e.g., the area of contact, pressure, temperature, test velocity, etc. [3]. The kinetic friction properties are believed by some researchers to be more important than the static ones for avoiding slips and falls on level surfaces [4, 5, 6].

Method

Workers are apt to fall while walking on roofs, in particular, if there is an uneven surface, like that of ceramic tile. Slide characteristics were measured, including those of tile roofs. The kinetic friction coefficient during roof falls treated in this study differs significantly from the friction coefficient described in elementary physics, where the surfaces are always in constant contact, without skipping. Intermittent-contact kinetic friction defines the Sliding-Resistance Coefficient (μ_{sr}) in this paper.

Theory of Measuring Sliding-Resistance Coefficient on Pitched Roof

In a previous study [7], kinetic friction coefficients of rubber, leather and neoprene sole materials were tested on sheets of poplar plywood, spruce, etc., by a drag-type slipmeter on a flat surface. Measured friction values between neoprene and the contacting surfaces exceeded unity.

This study examines actual sliding properties on a roof. The acceleration of a substance sliding on a roof surface, α (m/s^2), is obtained by the following equation, in which g represents acceleration of gravity (9.8 m/s^2), θ is the roof pitch (degrees), and μ_{sr} the sliding-resistance coefficient:

$$\alpha = g(\sin\theta - \mu_{sr}\cos\theta)$$

If the sliding velocity of a body on a roof is constant, it means that the sliding acceleration, α, is zero. The sliding-resistance coefficient μ_{sr} then reduces to the classical formulation:

$$\mu_{sr} = \tan\theta;\ \text{for}\ \alpha = 0$$

If the sliding velocity is accelerated at the rate of α, μ_{sr} becomes

$$\mu_{sr} = \tan\theta - \alpha/(g\cos\theta)$$

By measuring the sliding acceleration, α, and the roof pitch, θ, the sliding-resistance coefficient μ_{sr} can be calculated.

Four methods of measuring the slide acceleration, α, were considered in this study:
(1) Accelerometer,
(2) Cord extension with a pulse encoder,
(3) X-Y video tracker, and
(4) Measuring distances and elapsed times at three points passed by a sliding object.

Since, in cases of ceramic tile roofs, the dummy skips over the tiles (this phenomenon is caused by the uneven tile surface), sliding acceleration cannot be measured accurately by methods (1) and (4). Methods (2) and (3) were examined in preliminary tests. A cord-extension meter (as shown in Figure 1) was chosen because of its higher accuracy and efficiency. The velocity of the dummy is based on cord extension. The 'speed meter' with a pulse encoder produces 1000 pulses when the drum rotates once. Sampling interval is set at 2 ms, allowing for measurement precision within $^{+}/$-2 mm and extensions of up to 50 meters. Figure 2 shows a typical graph relating the slide-velocity as a function of time down a roof surface. The slope of the curve represents $^{\Delta V}/_{\Delta T}$, i.e., acceleration.

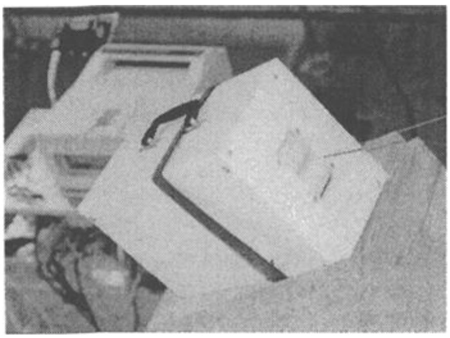

Figure 1. *'Speed Meter' (Pulse Encoder)*

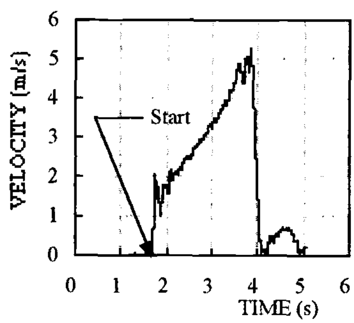

Figure 2. *A Typical Speed-Measurement Graph from the Speed Meter.*

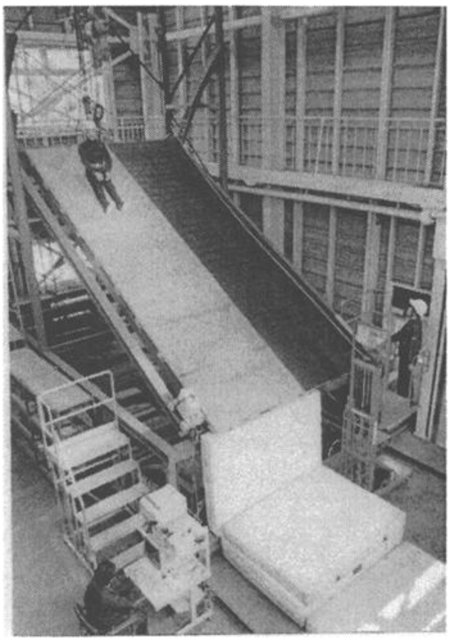

Figure 3. *The Pitched 'Test Roof,' Here Fit With Plywood Sheathing (left) and Slate Shingle (right).*

Adjustable Pitched Roof

The slopes of residential roofs in Japan range from 40% - 70%. Certain temple and shrine roofs exceed 100% (45 degrees). The simulated roof chosen for this experiment was 6.1 meters long and 3.1 meters wide, with a maximum inclination of 45 degrees, as shown in Figure 3.

Roofs of galvanized flat sheet metal, Japanese glazed ceramic tile, slate shingle finished with a sandy surface (thickness 5 mm), bitumen felt (thickness 1 mm, weight 1 kgf/m^2), and lauan plywood-sheathing were used for the experiments. The bitumen felt (also called "waterproof sheet") applied was cardboard impregnated with asphalt and sprinkled with sand. Rain was simulated by spraying water from the crown of the roof.

Footwear

Footwear used for the experiment was rubber-soled, split-toed Japanese construction worker's footwear (*jikatabi*), safety shoes with urethane soles, and rubber-soled sneakers. (See Figure 4.)

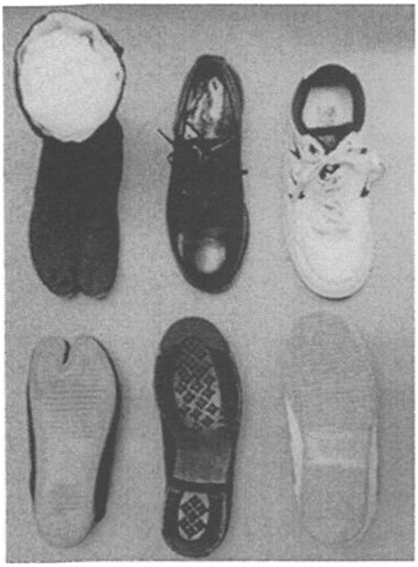

Figure 4. *The Tested Shoes.*

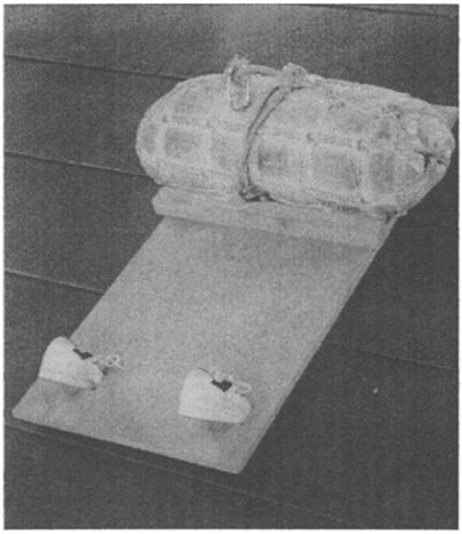

Figure 5. *The Test Jig: a Wood Panel with Tested Shoes on Sheet-Metal Roofing.*

Jikatabi soles featured a wavelike pattern, those of the safety shoes had a star-shaped tread, while the sneakers had a small rectangular tread. Observing roofers on sloped roofs revealed that they invariably brace themselves by contacting the slope with their toes. Based on this, a wooden panel for use in measurement was prepared so that front of the shoes could contact the surface of the roof. Rectangular holes were opened at four places, two in the upper and two in the lower part of the (1200 x 525 x 21 mm) wooden panel (See Figure 5), so that only the toes of four shoes could make contact. A sandbag weighing 75kg (700 mm long, around 250 mm in diameter) was placed on a wooden crosspiece located at two-fifths of the length between the panel's upper and lower holes. The design was intended to keep the sandbag away from the soles of shoes that were mounted at the lower holes of the panel.

Dummy

In the slide experiments, used to determine the clothing-to-roof friction, a worker was simulated by a dummy wearing a safety belt, a helmet, and new clothing manufactured from 60%-polyester/40%-cotton fabric. The dummy weighed 61 kg; its height was 167 cm. The influence of the 'dirtiness' of the clothing was not examined in this paper because of the complex nature of dirtiness: soil, oil, sand, wood powder, etc. In my experiments, the clothing was used until noticeable wear was observed. In order to allow the dummy to start from the crown of the roof; an electromagnetic separator was installed at the dummy's head. (See Figure 6.)

Figure 6. *The Test Dummy on Japanese Glazed Ceramic Tile Test Roof.*

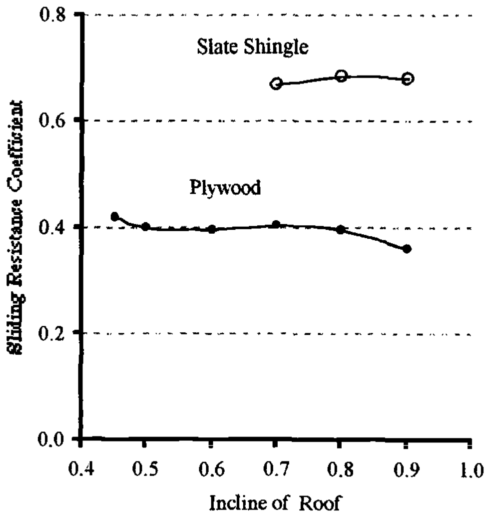

Figure 7. *Test Results Showing the Relationship Between the Angle of Inclination and the Coefficient of Sliding Resistance for Slate-Shingle and Plywood Roofs.*

Results

Sliding-Resistance Coefficient between the Dummy and Pitched Roof

The average value of the sliding-resistance coefficient was based on the results of five measurements (Figure 7). The coefficient of sliding resistance did not appear to be related to the roof-incline angle. Even though falling velocity rose, the coefficient of sliding resistance remained virtually the same.

The coefficient of variance ((standard deviation / arithmetic average) x 100) for the measurements was small, ranging from 2%– 6%. On that basis, I set the roof pitch according to the sliding- resistance coefficient of the individual roofs, rather than using a constant roof pitch. Specifically, the roof pitch was set slightly higher than the sliding-resistance coefficient of the roof surface under test. It should be noted that, with the slate-shingled roof (Figure 7), the sliding-resistance coefficient could not be measured when the pitch was 0.7 or lower as there was no sliding.

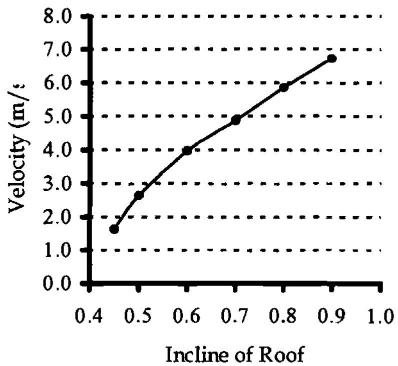

Figure 8. *Maximum Sliding Speed of Test Dummy as a Function of Roof Pitch (Plywood Roof).*

Because the position for hauling up the dummy was fixed by the apparatus, the sliding distance from the starting point to the eaves grew longer as the pitch became steeper. The dummy's maximum sliding speed thus increased in proportion to the roof pitch (Figure 8). Since the sliding-resistance coefficient was essentially independent of the roof-pitch angle, consistent sliding-resistance-coefficient values were generated independent of the slide velocity.

The sliding-resistance coefficient when the dummy fell was measured three times on each roofing material. The pitch was preset at 0.8 for waterproof sheet and slate-shingled roofs under dry conditions, 0.6 for plywood-sheathing and galvanized-sheet-metal roofing under wet conditions, and 0.7 for the remainder of the tests. As shown in Figure 9, under dry and wet conditions, the lowest sliding-resistance coefficient was recorded on sheet metal roof, with the highest on waterproof-sheet roof.

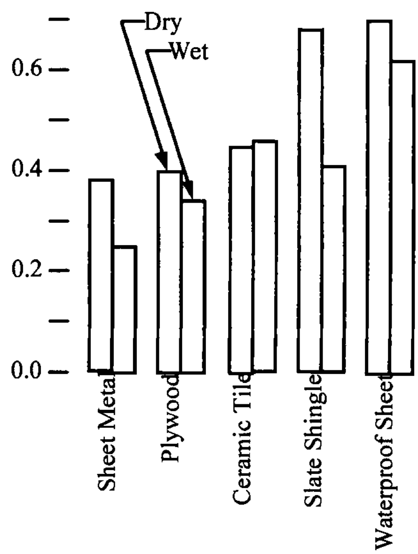

Figure 9. *Sliding-Resistance Coefficient Between the Dummy and the Different Roofing Materials, Wet and Dry.*

The difference between sliding-resistance coefficients under dry and wet conditions is important. For example, for the slate-shingled roof, μ_{sr} was 0.684 when dry, and fell to 0.411 when wet, a 40% reduction. (The reduction represents a value obtained by dividing the loss of sliding-resistance coefficient (Figure 9) obtained when dry to that when wet by the dry-condition coefficient, expressed as a percentage.) (See Table 1.) In this paper these ratios are called the Sliding-

Table 1. *Resistance Reduction Rate between Wet and Dry Roof Surface.*

Roof material	Reduction (%)
Sheet metal	36
Plywood	14
Ceramic tile	–
Slate shingle	40
Waterproof sheet	12

Resistance-Coefficient Reduction Rate, or simply, the Reduction. In the case of the sheet metal roof, for example, μ_{sr} dropped from 0.383 to 0.245, a reduction of 36%. Ceramic tiled roof showed very little difference in the sliding-resistance coefficient under wet and dry conditions. (When taking a plunge from this type of roof, the dummy fell in a skipping motion owing to the uneven surface of the tiles.)

Shoe-Friction Testing

Preliminary tests were conducted using the shoe-equipped jig on the pitched test roof under wet conditions. Of the five roofing materials, the three that were rough-surfaced, i.e., ceramic tile, slate shingle, and bitumen felt, gave adequate wet-surface traction. I therefore focused the testing on the plywood and sheet-metal roof surfaces, both of which—depending upon the sole material—have fairly low sliding-resistance coefficients. When the roof was wet, testing was conducted at a preset pitch of 0.6; when dry, the pitch was preset at 0.9.

For dry surfaces, little difference was seen in the sliding-resistance coefficient among footwear; moreover, that coefficient was high, from 0.77 to 0.84. (See Figure 10.) When wet, μ_{sr} fell sharply. The sheet-metal roof was more slippery than the plywood- sheathing roof. *Jikatabi* proved to have the weakest grip on sheet metal, while the sneakers had the highest.

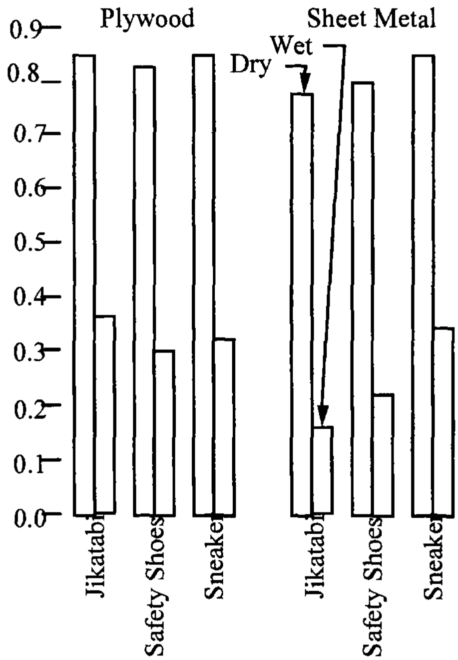

Figure 10. *Sliding-Resistance Coefficient Between the Three Tested Shoe-Sole Materials Against Plywood and Sheet-Metal Roofing.*

Table 2. *Slide-Resistance-Coefficient Reduction Rate between Wet and Dry Conditions.*

Footwear	Sheet metal	Plywood
Jikatabi	79%	56%
Safety shoes	72%	64%
Sneakers	59%	61%

Table 2 gives the reduction rate of sliding-resistance. The greatest reduction was seen in sheet-metal roofing with *jikatabi*. Next in magnitude were sheet metal with safety shoes and sneakers respectively. *Jiikatabi* and safety shoes, in particular, showed higher reduction rates. With the plywood-sheathing roofing, the reduction rate was 56% to 64%. Listed in decreasing order of reduction rate against plywood are safety shoes, sneakers and *jikatabi*.

Discussion

The Relationship between Shoe-Sole and Clothing Friction

Using the dummy, the sliding-resistance coefficient of clothing was lower than that of footwear in corresponding conditions. Thus, even under dry conditions, if a worker loses his stance, so that body weight cannot be supported by the shoe soles, the clothing-to-roof-surface friction coefficient is insufficient (except for waterproof sheet and slate) to prevent sliding off even a shallow roof.

Wet Roofing

Footwear plays a critical role in preventing workers on roofs from falling. Figure 10, to illustrate this point, shows that in the case of a sheet-metal roof, sliding-resistance coefficients as high as approximately 0.8 exist when the surface is dry. When the roof surface becomes wet, resistance to slipping fells precipitously, with the sliding-resistance coefficient plunging to a mere 0.16, a reduction of sliding resistance (considering *jikatabi* footwear) of 79%. As Table 2 shows, the rate of reduction was at least 50% in all cases. Thus, the difference in sliding-resistance coefficient of footwear between dry and wet conditions is noteworthy indeed.

As noted above, owing to the low sliding resistance of clothing, even if the roof is not wet, there is a danger of falling if one loses balance. As I have written, footwear thus plays a critical role in worker safety when working on a roof.

Ceramic Tile Roofing

The results of dummy-slide tests on ceramic tile roofing revealed little difference in sliding-resistance coefficient between wet or dry conditions, presumably because of the skipping impacts caused by the uneven tile surface.

Summary and Conclusions

The following results were obtained from the experiments on the sliding properties of roofs:

- From the slide experiment using the dummy, the sliding-resistance coefficient was essentially independent of the roof pitch.
- In the slide experiment using the dummy, the lowest sliding-resistance coefficient was recorded for sheet-metal roofing under both dry and wet conditions.
- The slide test on footwear recorded a sliding-resistance coefficient as high as about 0.8 under dry conditions, but when wet the coefficient fell to 0.3 or less. It was lowest for sheet-metal roofing.

- In the experiment using sneakers, sliding-resistance coefficient was relatively higher on the sheet-metal roofing.
- The reduction rate of footwear sliding resistance was in the range of 59-79% in the case of sheet-metal roofing and within from 56-64% for plywood-sheathing. The reduction rate for *jikatabi* with sheet metal proved to be the highest at 79%.

A major finding of this paper turned out to be the risks associated with sheet metal and plywood roof surfaces. If it should begin to rain while working on a roof, workers will find that the kinetic slip-resistance properties of roof surfaces suddenly decrease from about 0.8 to 0.2–0.4. Thus, slips are apt to occur while working on roofs when it starts to rain. Because static friction is generally greater than kinetic friction, recovery from such a slip is likely to be impossible.

Attention should be paid to the low sliding-resistance coefficient between the dummy's clothing and roof surfaces such as sheet metal and plywood under dry conditions, where the clothing friction under dry conditions is far lower than that of footwear. That implies that there is a likelihood of an uncontrolled slide down even in a gently-pitched, dry roof if a worker loses balance and the contacts the roof with the clothed body rather than the shoe bottom.

An interesting field of research is the construction of clothing with high-friction areas to prevent the worker going off a roof if a loss of balance occurs.

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H. Medoff,[1] D. H. Fleisher,[2] and S. Di Pilla[3]

Comparison of Slip Resistance Measurements between Two Tribometers Using Smooth and Grooved Neolite®-Test-Liner Test Feet

Reference: Medoff, H., Fleisher, D. H., and Di Pilla, S., "**Comparison of Slip Resistance Measurements between Two Tribometers Using Smooth and Grooved Neolite®-Test-Liner Test Feet,**" *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424*, M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: Differences in slip resistance measurements under dry and wet conditions on the same smooth walkway surface may occur when testing with a Neolite®[4]-Test-Liner (NTL) test foot using the PIAST [Slip Test Mark II] and VIT [English XL] tribometers. To investigate the causes of these differences, two sets of NTL test feet (smooth and grooved) for each instrument were cut from the same piece of material. Slip-resistance measurements were made under both wet and dry conditions. The same operator was used for each tribometer, an observer monitored each test, and all testing was performed in the same room at the same time. The walkway surfaces were commercial floor materials.

On dry surfaces, the measured slip resistance using the grooved test foot was the same or lower than the results using the smooth test feet. On wet surfaces, measured slip resistance using the grooved test feet increased slightly with the VIT and significantly using the PIAST. Averaged test results showed that the use of the grooved test feet on both instruments brought the readings these devices closer to each other; using the grooved test foot, the readings generated by the PIAST and VIT were not significantly different.

Keywords: slip resistance, tribometer, walkway surface, grooved test feet

Introduction

The objective of this study was to compare slip-resistance measurements made with the VIT and PIAST using both smooth and grooved Neolite® test feet on selected walkway surface materials—glazed ceramic and unglazed quarry tile—wet and dry. We hypothesize that similar slip resistance measurements would be obtained between the

[1] Associate Professor of Engineering, Penn State University, 1600 Woodland Rd., Abington, PA 19001
[2] President, David H. Fleisher, Inc., 426 Pennsylvania Ave, Suite 205, Fort Washington PA 19034
[3] Director of Product Development, ESIS Risk Control Services, 1601 Chestnut St., Philadelphia, PA 19103
[4] Registered Trademark of Goodyear Tire and Rubber Co., Shoe Products Division, Windsor VT 05089.

PIAST and on the VIT when a grooved Neolite® Test Liner (NTL) test foot is utilized on both tribometers.

ASTM Committee F13 on Safety and Traction for Footwear presently has two test methods that are appropriate for determining the slip resistance of walkway surfaces under wet or contaminated conditions:

- ASTM Standard Test Method for Using a Portable Inclineable Articulated Strut Slip Tester (F 1677), and
- ASTM Standard Test Method for Using a Variable Incidence Tribometer (F 1679)

The results of these friction-measuring instruments do not always agree with each other.

Background – Hydrodynamic Squeeze Theory

Hydrodynamic squeeze film theory has been used to model the frictional behavior of materials in contact under contaminated conditions, e.g., water between the NTL test foot and the walkway surface [1,2]. For a rectangular test foot, the following expression has been used to describe the forces, fluid properties, slider velocity, geometry and appropriate correction factors:

$$h^2 = \frac{6\,\mu\eta l^2 b K_e K_p}{F_v}$$

where

h = film thickness (at rear of slider),
K_e = correction factor related to $^b/_l$ (fluid is squeezed out from sides),
F_v = vertical force on slider,
μ = velocity of slider relative to walkway,
η = fluid viscosity,
l = slider length,
b = slider width, and
K_p = wedge taper factor.

If a square slider is assumed, $l = b$ and

$$h^2 = \frac{0.066\eta l\mu}{F_v}$$

For specific contaminant and slider dimensions, the fluid film thickness varies as the square root of the velocity. When the contaminant (fluid film) starts to resist some of the vertical force applied by the slider (or foot in walking), the frictional force decreases. Minimizing film thickness normally results in an increase in friction at the interface between the test foot and the test surface. Generally speaking, adequate traction cannot be obtained between the foot and the surface until the film that separates them is pushed away and/or broken. Therefore, a thicker film, *cet. par.*,reduces slip resistance more than a thin film.

The test foot used on the PIAST (a 3" x 3" square) is larger than the VIT (a 1-1/4" diameter circle). This suggests the volume of the liquid film between the test foot and the surface would be greater for the PIAST, and slip resistance would be decreased compared to the VIT. Also, the test foot of the PIAST is approximately parallel to the surface when it strikes, while the VIT test foot strikes at an angle. This difference in initial contact angle between a smooth test foot and a smooth test surface may allow the VIT's test foot to more readily displace the liquid film than the PIAST test foot.

Description of Materials

Test Feet Material and Preparation

Neolite®-Test-Liner[5] test feet for the PIAST and the VIT were cut from the same sheet (six inch by six inch by $^1/_4$ inch thick). The Shore A hardness was determined to be 92, tested in accordance with ASTM Test Method for Rubber Property-Durometer Hardness (D 2240).

A series of grooves approximately $^1/_8$ inch deep by $^1/_{16}$ inch wide, with lands approximately $^3/_{16}$ of an inch across, were cut into two of the test feet. The NTL pads were mounted to the tribometer test-foot holders with double-sided tape (figs. 1 and 2). The as-supplied surface finish (sheen) of the test feet was removed with 100 grit silicon carbide sandpaper, until a uniform dull appearance was obtained. The NTL test feet were then prepared with 180 grit sandpaper.

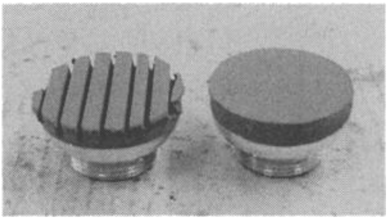

Fig. 1- VIT grooved and smooth test feet.

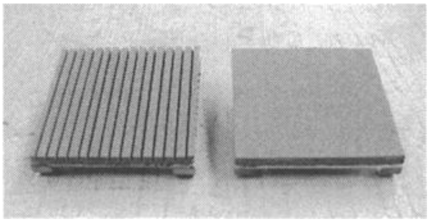

Fig. 2 - PIAST grooved and smooth test feet.

[5] Neolite Test Liner is available from Smithers Scientific Services, 425 W. Market Street, Akron Ohio 44303

Walkway Surface Material and Preparation

The walkway surface materials tested for slip resistance were 8-inch square glazed ceramic tile and 6-inch square quarry tile. The test tiles were secured to the floor using double-sided tape. Material of equal thickness to the test tiles was used to frame tiles to prevent movement during testing, and to properly adjust the height of tribometers (fig. 3). Each walkway surface was cleaned with Hillyard's Renovator and rinsed with distilled water.

Test Equipment

Test equipment was acclimated to the test site environmental conditions before the start of testing.

Test Conditions and Protocol

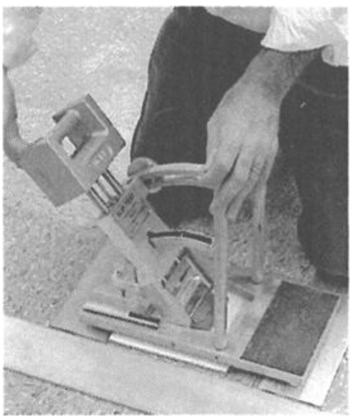

Fig. 3 – *PIAST (Slip Test Mark II).*

Testing with the PIAST (fig. 3) was performed in accordance with ASTM Standard Test Method for Using a Portable Inclineable Articulated Strut Slip Tester (F 1677-96). Testing with the VIT (fig. 4) was done in accordance with ASTM Standard Test Method for Using a Variable Incidence Tribometer (F 1679-00). All testing was done on the same day, in the same room, and under the same conditions. Temperature and humidity was monitored and recorded. Relative Humidity (RH) ranged from 29% to 31%. Temperature (F) ranged from 72°F to 75°F. The same operator conducted testing for each device. Each tribometer operator had an observer/assistant, who monitored the testing and recorded the results on a worksheet.

The grooved test feet were oriented in the direction of slip. Because the VIT test foot can rotate with contact during testing, its test foot was marked and monitored to maintain the same groove orientation.

To eliminate potential changes in the walkway surfaces that may have resulted from testing, the sequence of using each device on a given surface was alternated. For example, while the PIAST was being tested on the glazed ceramic tile dry with a smooth test foot, the VIT was being used concurrently on the quarry tile with the same

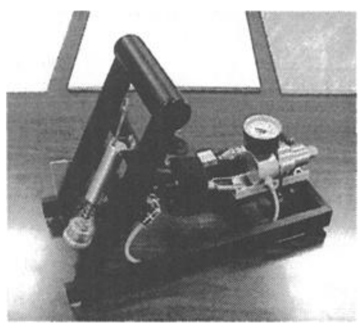

Fig. 4 – *VIT (English XL).*

test foot configuration. Dry testing was completed before wet testing commenced.

At least one set of four (4) slip resistance determinations was made for each condition. In most instances, at least two sets of four (4) determinations were made for each condition, e.g., dry, glazed ceramic tile using the VIT with a smooth foot represents one condition. A total of 116 data points were obtained in this study:

- VIT: 32 tests (Quarry), 24 tests (Ceramic) = 56 tests
- PIAST: 32 tests (Quarry), 28 test (Ceramic) = 60 tests

Results

The results show that the measured slip resistance of the grooved test feet versus the smooth test feet was found to be dependent upon the tribometer, the walkway surface material, and the environmental condition (wet or dry). Data was statistically analyzed using the Newman-Keuls Multiple Comparison Method. The tables below give the average friction coefficients. Significance was set at a p-value of 0.05 or less (Shaded boxes indicate no significant differences). The results follow[6]:

Wet Quarry Tile

	VIT	PIAST
Smooth	0.78	0.14
Grooved	0.85	0.87

Wet Glazed Tile

	VIT	PIAST
Smooth	0.18	0.01
Grooved	0.35	0.32

Dry Quarry Tile

	VIT	PIAST
Smooth	0.94	0.91
Grooved	0.95	0.93

Dry Glazed Tile[7]

	VIT	PIAST
Smooth	--	1.08
Grooved	--	0.77

Conclusions and Recommendations

An analysis of these limited results suggest that the use of a grooved test foot as compared to a smooth test foot effected the measured slip results of the PIAST more than the VIT. Importantly, with grooved test feet, both tribometers under wet and (to the extent that the tribometers gave results within their range) dry conditions, gave numeric

[6] For both tribometers, some of the individual readings appeared to be outliers. We believe that these outliers stem from two conditions:
The beginning of wet testing showed higher results, and then stabilized. We hypothesize that this phenomenon was due to saturation of porous surfaces
and initial wetting of the NTL;
Using new sandpaper in one instance yielded higher slip resistance readings.

[7] Certain dry readings on glazed ceramic tile were out of range for both instruments (e.g. greater than 1.0 for VIT, 1.1 for PIAST). These are indicated by a "--" As a result, no statistical analysis could be performed.

results that were not statistically distinguishable.

On the smooth walkway surface (glazed tile) under wet conditions, grooved test feet have more of an effect on measured slip resistance than smooth test feet. This may be a result of the grooves allowing the escape of the contaminant (water), thus breaking up the continuous hydrodynamic film between the test foot and the walkway surface. The rougher walkway surface material, i.e., the quarry tile, may act to break up the contaminant film by virtue of its own asperities, reducing the importance of whether or not the test foot is grooved.

While more testing needs to be conducted on these and other walkway surfaces, these preliminary results suggest that measurement consistency between the instruments would be improved by the use of grooved test feet.

Correlation of the results of these test methods with respect to biofidelity, i.e., with the parameters associated with human ambulation, is outside of the scope of this study.

No attempt has been made to quantify the effects of the test-foot grooving parameters, e.g., the depth, consistency, geometry, shape, and land size. Further study is needed to analyze the performance of these instruments using various test foot designs.

Acknowledgements

We wish to thank Dr. David Underwood, for completing the statistical analysis of the data, Dr. Robert Brungraber P.E., for preparing the Neolite® Test Liner test feet, Richard E. Daniels, P.E., for assistance in completing the testing.

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Robert H. Smith[1]

Examination of Sticktion in Wet-Walkway Slip-Resistance Testing

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Reference: Smith, R. H., "**Examination of Sticktion in Wet-Walkway Slip-Resistance Testing,**" *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424,* M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: Under certain circumstances, the measured slip resistance of wet walkways has been found to be greater than readings obtained from the same surfaces when dry, a seemingly anomalous result. This phenomenon, sometimes termed sticktion, is most often seen when using a leather test foot. Sticktion has been ascribed to surface-tension adhesion. Surface-tension adhesion is examined with a focus on its production in wet-walkway slip-resistance testing. Past research has indicated that surface hardness is a determinant of frictional resistance. A hypothesis is proposed that, when using leather test feet on wet surfaces, a large portion of the increase in readings over dry values is attributable to water-absorption softening of the leather, and constitutes real slip resistance. Reinterpretation of wet-leather test results as an indication of the presence of sticktion is suggested. Water must physicochemically 'wet' both the test foot and test surface for surface-tension adhesion to develop. Tests reveal that such wetting takes place on a number of test-foot and shoe-sole materials of interest. However, for surface-tension adhesion to be of significant magnitude in tribometry, a number of critical conditions must be present. The likelihood of significant surface-tension adhesion occurring when measuring slip resistance is assessed.

Keywords: slip resistance, sticktion, surface-tension adhesion, hardness, roughness.

Introduction

Slip-resistance measurements obtained with leather test feet often produce high readings on smooth, wet surfaces in comparison to the same surfaces when dry. This phenomenon is sometimes called sticktion. Sticktion has been attributed to surface-tension adhesion, associated with the squeezing out of water between the test foot and test surface. This paper examines the mechanism of surface-tension adhesion production in slip-resistance testing. Its objective is to assess the likelihood of significant surface-tension adhesion occurring in contemporary slip-resistance tribometry.

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[1]Engineer, National Forensic Engineers, Inc., P.O. Box 82486, Kenmore, WA, 98028.

Leather Test Foot Use in Slip-Resistance Metrology

Historically, higher slip resistance values obtained from a wet surface compared to those from the same surface when dry have often been found when using leather test feet.

In 1943 and 1948, Sigler published extensive friction research findings [1, 2] derived from floor testing with his dynamic device. Results obtained for dry surfaces often appeared indicative of their relative slipperiness. However, values produced on the same surfaces when wet were usually higher. This was especially so for smooth floors. All readings were obtained with leather test feet.

In 1970, Irvine presented static slip-resistance test results for leather soles on steel [3]. He reported that dry leather can be hard and slippery but becomes softer through water absorption from a wet test surface, and yields higher readings.

In 1982, Chaffin and Andres evaluated three tribometers fitted with leather and composition rubber test feet on three flooring surfaces; vinyl tile, concrete, and wood [4]. They found questionably high static coefficient readings which were noticeable only when the floor was wet and a leather test foot was used.

Irvine's observation that leather becomes softer as it absorbs water during testing is a common consequence of water absorption into porous materials. It appears appropriate to investigate both this water-softening effect in leather and the general influence of surface hardness when measuring walkway slip resistance.

Surface Hardness Influence on Slip Resistance

In 1974, Braun and Roemer measured coefficients of friction obtained through use of the Hoechst device developed for laboratory studies of floor treatment materials [5]. Issues investigated included differences in dry static slip resistance when using a given test foot on surfaces of different hardness. They determined static friction coefficients and Shore-D hardness of five unidentified floor tiles to which no floor treatment material had been applied. As the Shore-D hardness of the tiles decreased from 74 to 38, the dry coefficients increased from 0.18 to 0.44. This inverse relationship was more pronounced following application of a polish, presumably because of its softening effect. They reported that the average slip resistance of all untreated tiles was 0.32 and increased to 0.45 after polish application. In all of these tests, the test foot surface was mechanically lapped chromium. A test surface of lower hardness will often provide higher slip resistance compared to one of greater hardness when the test foot material and its hardness are unchanged.

The corollary to the above is also true in some circumstances; as the test foot hardness is decreased, the measured slip resistance of the test surface increases. This was illustrated in a 1978 paper by Braun and Brungraber addressing differences in slip resistance of certain walkway materials when each was tested with test feet of different hardness [6]. Such results were obtained when the Hoechst and the Brungraber Mark I Portable Articulated Strut Tribometer (PAST) devices were compared. Table 1 presents a portion of their data. It is seen that for both devices, the static slip resistance values found for the various dry test surfaces with a leather test foot were higher than for the lapped chromium test foot, both with and without polish.

Table 1 – *Dry static slip resistance values with chromium and leather test feet.*

Test Surface	Polished	Chromium Test Foot Hoechst	Chromium Test Foot PAST	Leather Test Foot Hoechst	Leather Test Foot PAST
Soft PVC[1]	No	0.33	0.37	0.53	0.58
Soft PVC	Yes	0.41	0.38	0.61	0.67
Rigid PVC	No	0.29	0.31	0.61	0.60
Marble	No	0.20	0.18	0.63	0.65
Plastic A[2]	No	0.74	0.64	0.86	0.78
Plastic B[2]	No	0.49	0.50	1.36	1.33
Plastic C[2]	No	0.44	0.50	0.71	0.88

[1]PVC = Polyvinyl Chloride
[2]Not Identified

Leather Water-Absorption-Softening Hypothesis

It is hypothesized that apparently anomalous readings produced during wet-leather tests result in part from softening of the leather as it absorbs water from the surface. The softer test foot is hypothesized to produce higher slip resistance by conforming more readily to asperities of the test surface resulting in greater their deformation. To assess this, direct comparisons of dry- and water-softened leather on the same surfaces were carried out using the Variable Incidence Tribometer, ASTM Standard Test Method for Using a Variable Incidence Tribometer (VIT), (F 1679-96). The VIT is an articulated strut-like device powered by compressed gas that applies a constant force to the strut at each activation. The test foot is applied to the test surface at controlled angles until slip occurs. The tangent of the angle just before slip is taken as the static slip resistance.

The leather conformed to US Federal Specification KK-L-165C. Tests on dry surfaces were done first with leather that had not been previously exposed to water. The as-received leather was prepared by sanding with 320 grit aluminum oxide paper. The test surfaces were polished marble with no floor-treatment-material coating, textured vinyl sheet-flooring, unpainted smooth sawn pine, and precast concrete stepping stones.

These dry surfaces were then tested with the same leather test foot after it had been soaked in water for one minute. Moisture drops on the test foot surface were removed before its use. (The test foot was wrapped in an impermeable membrane between testing of the four surfaces to prevent evaporation of water from the leather.) During testing no transfer of water from the leather to the dry test surfaces took place. Since no water film was present between the two surfaces, sticktion could not occur.

Table 2 presents these results. It is noted that all slip-resistance readings using soaked leather were greater than associated dry (unsoftened) leather values. Wet increases were much greater for the smoother marble, vinyl, and wood, compared to the rough concrete. This is consistent with test results by others [1, 2] on wet surfaces using leather test feet in which the largest relative wet increases occurred on the smoothest test surfaces.

To obtain an indication of KK-L-165C leather's water-absorbing ability, a sanded piece substantially identical in size and shape to the VIT test foot used above was soaked in tap water for 24 hours. Its dry weight was 4.4 grams. After soaking its weight was 6.1 grams, a difference of 1.3 grams, about 29%.

Table 2 – *Comparison of leather slip resistance values utilizing the VIT*[1]

Test Surface	Dry Leather	Soaked[2] Leather	Percent Increase
Marble	0.33 (0.01)[3]	0.57 (0.01)	73%
Vinyl	0.36 (0.01)	0.47 (0.01)	31%
Wood	0.41 (0.01)	0.67 (0.01)	63%
Concrete	0.75 (0.01)	0.77 (0.01)	3%

[1]ASTM F 1679-96
[2]Soaked in tap water for one minute.
[3]Standard deviation

Characterizing the Surface-Tension Adhesion Mechanism

History of the Surface-Tension Adhesion Hypothesis in Slip-Resistance Tribometry

Identification of surface-tension adhesion as a mechanism thought to be present in wet-walkway testing seems to have begun with Brungraber's 1976 overview [7] of slip-resistance research. In this he cited findings presented at a 1952 conference arranged by the US National Research Council on the structure and properties of solid surfaces. The portion of the findings concerning general issues in friction development on such surfaces were reported in the conference proceedings by Bowden and Tabor [8]. Brungraber hypothesized that a mechanism discussed by Bowden and Tabor also occurs in slip resistance tribometry. They reported that, in some cases, thin water films between solid surfaces can produce strong forces resisting relative movement of these surfaces. This was observed by measuring the adhesion of two clean, flat glass plates put in contact in dry air. Their adhesion was found to be negligibly small. However, when a small drop of water was placed between the two parallel surfaces, strong adhesion forces developed. It was determined that these forces did not arise from inherent resistance to motion of the glass plates. Rather, they could be entirely accounted for by surface-tension adhesion forces in the water film. Such high resistance to motion was also found with thin, interfacial films of water between two parallel, curved surfaces, such as spheres of opposite curvatures, placed next to each other. It is also hypothesized in this paper that surface-tension adhesion can be present in slip-resistance tribometry of wet walkways.

Surface-Tension Adhesion Effects: Background

Surface-tension is a manifestation of surface energy and is observable through development of menisci between solid surfaces. It causes liquid drops to be spherical and allows the production of soap bubbles. It provides the capillarity in plant pores required to draw nutrients in solution from their root systems. The angle of contact, θ, of a liquid on a solid is considered a measure of the liquid's adhesion to that solid [9]. Surface-tension adhesion develops in concrete products through evaporation of water from pores, producing shrinkage and frequently, cracking. Surface-tension adhesion forces within the pores can exceed the tensile strength of concrete during drying [10].

Rabinowicz discusses surface-tension adhesion in magnetic recording systems, termed 'stiction' in that field [11]. For stiction to occur, smooth surfaces in close conformity with a liquid film at their interface are required. As examples, he cites a smooth, flat head against a smooth, flat tape, rigid disk, or diskette. He derived relationships between the primary variables in surface-tension adhesion: the distance between the two solids, the surface tension of the liquid, and the degree of its adhesion, θ, to each solid surface.

Physicochemical Wetting in Surface-Tension Adhesion Development

For surface-tension adhesion to occur in wet-walkway, slip-resistance testing, surface tension must develop between the two solid surfaces. An important issue in surface tension development is whether the liquid 'wets' or adheres to the solids in question in the physicochemical sense. When a liquid does not wet a solid surface, $\theta > 90°$, the force of attraction of the liquid molecules toward the solid (the adhesive force) is less than the force tending to draw them back into the liquid (the cohesive force). When a liquid wets a solid surface, $\theta < 90°$, the liquid molecules at the interface are attracted by the solid more strongly than they are attracted back into the liquid [9].

The molecular attractive force of a liquid toward the test surface and test foot must be greater than the cohesive force of the liquid if surface tension is to develop in tribometry. If it is considered that sticktion is surface-tension adhesion, then the liquid must physicochemically wet both the test foot and test surface in order for sticktion to arise.

As mentioned by Shortly and Williams, surface-tension adhesion forces are applied through variably curved menisci between two solid surfaces [9]. The radius of curvature of a meniscus and the force it produces depend, in part, on the distance between the two solids. The smaller the radius of curvature, the larger the adhesion force.

Surface-Tension Adhesion Between Glass Plates

As an example of liquid molecules which adhere strongly to a solid by surface tension, Shortly and Williams discuss water on a glass plate [9]. They found that a drop of water placed on clean glass will spread until becoming a layer one molecule thick. Preliminary investigation with KK-L-165C leather demonstrated plate glass to be an effective surface on which to assess the wettability of materials of interest, and their potential for sticktion development.

An effort was made to become familiar with the critical variables involved in surface-tension adhesion production between two flat surfaces as they are relevant to slip-resistance testing. In this regard, two clean 2" (50.8 mm) x 2" x ¼" (6.4 mm) glass plates were used to produce visually observable, menisci-solid surface interactions.

Water was flooded over one plate and then a top plate placed on it. By lifting the top plate, a visible, perimeter meniscus was produced. Lifting this plate to keep it horizontal caused the assemblage to move upward as surface-tension forces in the meniscus retained the bottom plate. However, the slightest tilt caused the bottom plate to slip sideways and fall. There was insufficient adhesion to unitize the assemblage against shear forces. Were these plates a test foot and test surface, a significant surface-tension adhesion force would not have been present.

Reducing the water film thickness between the two glass plates, allowing them to come more closely together, increased surface-tension adhesion. Hand pressure was applied to the top plate to squeeze out as much water as possible. Significant adhesion, gauged by resistance to sliding of the two plates, developed.

Adhesion was further increased by sliding the top plate relative to the other, blotting water from the surface just exposed, and sliding the top plate back over the just-exposed area. Repeating the procedure four to five times increased the surface-tension adhesion forces to the degree that relative movement between the two glass plates could not be accomplished manually. This procedure to remove sufficient water from between two surfaces allowing large surface-tension adhesion forces to develop is here called smear-thinning.

Assessing the Wettability of Selected Tribometer Test-Foot and Shoe-Sole Materials

Selected common test-foot and commercially available shoe-sole materials were investigated for wettability. Samples 1.25" (31.8 mm) in diameter and 0.2" (5.1 mm) thick were utilized. All samples had been sanded with progressively finer sandpaper, finishing with 400 grit aluminum oxide paper, so as to employ a consistent surface. Prior to this sanding process, the tread patterns on the commercial heels had been completely removed. The test-foot materials were a commercial leather (crust not removed), KK-L-165C leather (crust not removed), KK-L-165C leather (crust removed), and Neolite® test liner[2]. The shoe-bottom materials were hard plastic, high-plastic-content, neoprene, nylon-neoprene, and rubber.

All the selected materials were put in contact with a clean glass plate with a drop of water between them. All materials were wetted by water. Such wetting was readily visible in the form of menisci attached to both the glass and selected material samples. The samples were seen to adhere without movement to the wet underside of the glass plate when it was oriented horizontally so the menisci forces were in tension. Similar adhesion was noted when the glass plate was oriented vertically so the menisci forces were in shear.

[2]Goodyear Tire and Rubber Company, Akron, OH.

Smear-Thinning Assessment of the Selected Test-Foot and Shoe-Sole Materials

In the limit, when two solid surfaces are in contact, actual physical bearing need be at three asperities only. The distance between solid surfaces at locations where asperities do not contact depends on the height of the contacting asperities. When considering test feet and test surfaces in slip-resistance tribometry, the method of preparing the test foot becomes relevant as it affects surface roughness (asperity height, distribution, and sharpness). Historically, the method of preparing the test foot in regard to roughness has not always been reported.

The likelihood of significant surface-tension adhesion occurring with the selected materials prepared in the described manner was assessed utilizing a glass plate and the smear-thinning technique. The plate was flooded with tap water and a test sample placed on it. Hand pressure was used to squeeze out as much water as possible. Slight surface-tension adhesion was present with each of the materials as described above. However, it was judged by manual application of shear to be too small in each case to be significant when compared to shear forces applied by modern slip-resistance tribometers of up to hundreds of newtons [12].

The smear-thinning technique against the glass plate was then applied to each material. None of the materials were very susceptible to this approach. Shear resistance did not increase to a significant degree. It appears likely that at least two factors were at work. The surface roughness of the tested materials produced by final sanding with 400 grit aluminum oxide paper may not have been optimum for maximum surface-tension adhesion development. Alternatively, or in combination, water may simply not be very strongly attracted to these materials.

Surface Roughness Considerations in Surface-Tension Adhesion Development

Surface Roughness and Maximum Surface-Tension Adhesion Development

It is desirable to quantify the degree of surface roughness allowing the maximum surface-tension adhesion to develop with slip-resistance test materials of interest. This can be accomplished through use of a profilometer. Rabinowicz reported experimental studies in the magnetic recording industry involving rigid disks which found that the greatest surface-tension adhesion is present when the thickness of the liquid layer is approximately equal to the root-mean-square surface roughness of the magnetic medium [11]. This is consistent with the hypothesis that when surface-tension adhesion is maximum, the void volume between the two solid surfaces, in contact only at their asperities, is filled with liquid. This void volume encompasses that which exists between the asperity peaks and valley bottoms of the two solid surfaces as they interact together. The root-mean-square roughness is a measure of the average deviation of the determined asperity profile from its averaged or nominal height. The experimental work reported by Rabinowicz included root-mean-square roughness values as small as 2 nm, a distance equal to approximately six water molecule diameters.

Surface-Tension Adhesion of Neolite® and Leather Under Varying Roughness Conditions

An assessment of Neolite's® surface-tension adhesion capabilities under varying roughness conditions was carried out using the smear-thinning technique. Two pieces of clean, as-received Neolite® (whose surfaces had not been altered in any way) were wetted with water while oriented horizontally, and then pressed together. The volume of water used was sufficient to ensure that some was squeezed out around the periphery. This was done so the void volume between the asperities of the contacting surfaces was completely occupied by water. Smear-thinning was then manually applied, the same procedure previously carried out with the single piece of sanded Neolite® and a glass plate. No significant surface-tension adhesion developed between the two pieces.

Two VIT test feet fitted with Neolite® were then utilized in the smear-thinning procedure after sanding with aluminum oxide paper to vary their degree of roughness. Sanding began with 400 grit, and included 320, 220, 120, 100 and 80 grit paper. The procedure involved sanding each test foot in a circular motion with a radius of 60 mm, 25 times in each direction. The two test feet were brushed free of sanding residue, wetted, pressed together in the manner described above, and smear-thinning applied. No significant surface-tension adhesion between the two test feet developed when sanded with 400 grit paper. The smear-thinning technique was then employed on plate glass with each test foot. No significant surface-tension adhesion arose between the test feet and the glass plate. These same procedures were then carried out for each degree of roughness for the two test feet together, and the test feet on a glass plate. Again, no significant surface-tension adhesion developed in any of these assessments.

Throughout this assessment, the manually-sensed surface-tension adhesion between the test feet themselves (Neolite® to Neolite®) did not perceptibly change. However, there was a noticeable increase, and then decrease, in the sensed surface-tension adhesion between the test feet and plate glass. Though the increase was not sufficient to be significant in slip-resistance tribometry, it suggests that the degree of roughness at which Neolite® exhibits maximum surface-tension adhesion with water on plate glass was included within the assessed range. The surface-tension adhesion of Neolite® against a glass plate increase from the as-received condition to a maximum at 320 grit. Thereafter, the degree of adhesion decreased.

The smear-thinning procedure using the Neolite® test feet after sanding was also carried out against glazed ceramic tile and the marble mentioned above. For both materials, surface-tension adhesion of the Neolite® increased from the 400 grit roughness to 320 grit, but remained insignificant. Adhesion thereafter decreased.

It is noted that the greater surface-tension adhesion between Neolite® and plate glass, glazed tile, and marble, as compared to Neolite® against itself, is consistent with the general nature of such adhesion. The total surface-tension adhesion force between two solids with a liquid film between them is proportional to the sum of the adhesion force between the liquid and one solid, and the liquid and the other (possibly different) solid. Surface-tension adhesion does not conform to the 'weakest-link' behavior model [11].

The smear-thinning procedure utilizing KK-L-165C leather against a glass plate was also carried out with the same varying roughness conditions produced by sanding. It was found that as-received KK-L-165C leather exhibited only very slight adhesion. However, a noticeable increase in surface-tension adhesion was produced by sanding with 400 grit paper. This adhesion increased through 320 grit to 220 grit sanding. It decrease thereafter.

The same smear-thinning procedure was carried out using another piece of KK-L-165C leather against glazed ceramic tile and the marble mentioned above. For both materials, surface-tension adhesion of the leather increased from the smooth, as-received condition, to the roughness condition associated with 220 grit sanding. Adhesion thereafter decreased.

The magnitude of the surface-tension adhesion experienced by the subject leather at 220-grit roughness against the three surfaces appears to be potentially significant in slip-resistance tribometry.

Discussion

To advance wet-walkway safety, it is necessary to proceed on a correct scientific basis. Understanding the science of friction measurement is essential. The effects of leather softening by moisture absorption, and surface-tension adhesion development, need to be accurately and completely characterized so they may be addressed properly as related safety issues arise. An attempt has been made here to apply the basic principles of surface tension to the findings of the present and previous slip-resistance testing.

Water-Absorption Softening

The present work indicates that water-absorption softening plays a significant role in slip-resistance tribometry, at least in testing of wet surfaces with leather. It appears that softening of test feet during testing of wet surfaces should be of general concern in regard to data interpretation.

Surface Tension and Viscosity of Water

Surface tension exists in all liquids [9]. Its magnitude effects the significance of any surface-tension adhesion which may develop. Water possesses surface tension to a high degree, 73.05 dynes/cm at room temperature. Of the 126 most common substances that are liquid at room temperature, its surface tension is third greatest, exceeded only by hydrogen peroxide (76.1 dynes/cm) and hydrazine (91.5 dynes/cm), a rocket fuel [13]. As a practical consideration, it is most likely that water will be the liquid involved in any stiktion encountered in contemporary tribometry.

Sometimes surface-tension adhesion and viscosity are of simultaneous practical concern when a thin liquid film is between two solid surfaces. Rabinowicz has developed equations addressing viscosity in the analyses of such conditions [11]. When viscosity is at issue, time of force application is a relevant variable. In his analyses of viscosity and surface-tension adhesion acting together, Rabinowicz selected a time of one second, after which water usually no longer remains a coherent film. Using a location where two asperities are in contact as an example, he determined that the resistance to tangential movement by the viscous force of water would be about 0.17 dyne. However, resistance to relative motion from surface-tension adhesion at this location would be in the gram (980.7 dynes) range. Viscosity is not considered in the present paper.

Testing of Wet Surfaces with Leather Test Feet

Assessment of wet-walkway slip resistance with leather has often been avoided because of the sticktion concern. Inasmuch as leather is a commercially available shoe-sole material, it appears desirable to undertake a comprehensive examination of its slip resistance under various water-exposure conditions. It is noted that further tests by this investigator not detailed here indicate that the degree of softening of leather during any one contact with water, and slip-resistance test results given by that sample, are dependent on the nature of any such previous contacts.

Smear-Thinning

Based on the present findings, it appears that smear-thinning, using the particular test-foot material of interest against the associated test surface, is a simple and practical means by which an indication of the potential for the development of surface-tension adhesion in the given conditions may be made.

Likelihood of Surface-Tension Adhesion Development in Contemporary Tribometry

The present work suggests that reinterpretation of seemingly anomalous wet-leather test results as an indication of the presence of sticktion is appropriate. It is not necessarily true that surface-tension adhesion will always develop under wet conditions with a smooth, flat, test surface, and ample time for squeezing out of water. Wettability of the test foot by the liquid involved, as indicated by the Neolite® assessments, is a relevant consideration.

Because as-received Neolite® test liner, and such test liner roughened as described, do not show significant surface-tension adhesion during smear-thinning against plate glass, the subject glazed ceramic tile, or marble, it does not seem likely that significant surface-tension adhesion could occur with Neolite® prepared by contemporary techniques. However, this possibility should be assessed in the field using the test liner on whatever test surfaces are of interest.

The presence of significant surface-tension adhesion also depends on the ability to develop a sufficiently thin liquid film. Smear-thinning utilizes blotting for this purpose. During actual testing blotting is not usually involved. Also, sufficient dwell time is required. It appears possible that horizontal pull meter tribometers, if testing a wet surface to emulate a pedestrian's foot slipping from a wet surface to a dry one, might reproduce the smear-thinning process and effect. Further, it appears possible that the Horizontal Dynamometer Pull-Meter, ASTM Standard Tests Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method, (C 1028-96), which employs a 22 kg (50 lb) weight on a drag sled possessing a 3" (76.2 mm) x 3" test foot, may reproduce smear-thinning on smooth, wet surfaces without the necessity of being pulled onto a dry surface.

It is common in contemporary wet tribometry to test such that 'ponding' of the appropriate liquid on the test surface of interest is attempted. The test foot is then applied within the liquid. Surface-tension adhesion cannot develop if the contacting surface of the test foot is completely beneath the liquid surface. An air-liquid interface beneath the test foot itself must be present.

Based on the hypothesis that significant sticktion is present in most wet-leather testing, some previous slip-resistance measurements obtained with test feet other than leather have been used to hypothesize the presence of significant sticktion in such tests. Certain tribometers have been designed to prevent such hypothesized sticktion. It appears appropriate to reevaluate these considerations so that readings given by test feet other than leather can be completely interpreted with reasonable scientific assurance.

The smear-thinning assessments employing plate glass, glazed ceramic tile, and polished marble suggest that Neolite® exhibits its maximum (but insignificant) surface-tension adhesion when roughened with 320 grit paper, while KK-L-165C leather exhibits its greatest surface-tension adhesion when roughened with 220 grit paper. These findings indicate that maximum surface-tension adhesion development with test-foot materials occurs at a particular degree of roughness, which might not be characterized as smooth. Research on appropriate test foot preparation techniques appears needed in this regard.

Surface Roughness Considerations

Surface roughness is a determinant of friction. It is desirable to be able to sense its effects in slip-resistance tribometry. Studies of surface roughness as it relates to walk-way slip resistance have been carried out by Chang [14]. This involved testing with five different tribometers fitted with Neolite® test feet (including the VIT employed in the present testing of leather) under different roughness conditions to determine their sensitivity to this property. The other devices were the James Machine, ASTM Standard Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine, (D 2047-93), the Horizontal Pull Slipmeter, ASTM Standard Test Method for Using a Horizontal Pull Slipmeter (HPS), (F 609-96), the Portable Inclineable Articulated Strut Slip Tester, ASTM Standard Test Method for Using a Portable Inclineable Articulated Strut Slip Tester (PIAST), (F 1677-96), and the Sigler pendulum tester [2]. Chang assessed 21 surface roughness parameters measured by a profilometer. He determined that the VIT was sensitive to the effects of surface roughness to a higher degree than the other devices. The two most correlated parameters in dry VIT testing were the arithmetical mean of asperity heights and the average of their maximum heights above the mean.

The increased slip resistance of the test surfaces when measured by water-softened leather is hypothesized to arise from the leather's resulting ability to conform more readily to the test surface asperities, thereby producing greater resistance to shear deformation in the test foot. This hypothesis is consistent with the results presented in Table 2. The slip resistance of concrete when measured using the softer test foot showed an increase of 3%. The other, much smoother, test surfaces exhibited increases ranging from 31% to 73%. This suggests that asperities on the rougher concrete were penetrating into the harder leather test foot to a considerable degree before softening, but that the smaller asperities on the smoother test surfaces were not.

The hypotheses is also consistent with the behavior of smooth metal when abraded by corundum, natural Al_2O_3. Avient, Goddard and Wilman [15] abraded eight metals; Al, Ag, Cu, Pt, Fe, Mo, U, and W with corundum paper having mean particle diameters of 5, 10, 15, 25, 35, 45, 70, 100 and 150 microns. The coefficient of friction of these metals abraded using 150-micron paper increased by 0.10 to 0.15 as compared to no abrasion.

In most uses of metal where dynamic friction is of concern the surfaces are so smooth that little contribution from roughness develops. The classical metallic friction expression is $\mu = F_T/F_N$, where μ is the coefficient of friction, F_T is the tangential frictional-resistance force, and F_N is the applied normal force. This expression is valid only when the frictional contribution from roughness may be ignored as negligible [11].

When significant roughness is present its contribution must be added to account for all friction sources. Rabinowicz [11] derived an expression for the roughness contribution, $\tan \theta/\pi$, where θ is the mean roughness angle of the abrading asperities on the harder of the two surfaces involved. The classical coefficient-of-friction expression then becomes

$$\mu = F_T/F_N + \tan \theta/\pi.$$

It appears appropriate to identify and quantify frictional contributions from surface roughness when interpreting and applying slip-resistance test results.

The Table 2 data suggest that much of the initial slip resistance of the smoother materials when tested with the harder leather arose from a significant source not associated with roughness. As reported by Bowden and Tabor, the principal friction mechanism between two smooth metal surfaces is strongly adhering surface atoms at the areas of their contact (dry adhesion) [8]. It is probable that, as in metals, dry adhesion between contacting surface atoms in test feet and test surfaces makes a significant frictional contribution in slip-resistance tribometry.

Conclusions

The present results, and those reported by Rabinowicz [11], are consistent with Brungraber's hypothesis [7] that the adhesion mechanism of the phenomenon some have subsequently called sticktion, is surface-tension adhesion.

If water does not physicochemically wet both the tribometer test foot and the test surface, surface-tension adhesion between them cannot occur.

The present results indicate that surface roughness and the degree of wettability of the test foot and test surface are primary considerations in surface-tension adhesion development in tribometry.

Dwell time, and some means to expel sufficient liquid, are required to produce a thin film for surface-tension adhesion to be significant in tribometry.

It is not likely that significant surface-tension adhesion will occur with a Neolite® test foot prepared by contemporary techniques.

The present results indicate that leather softening due to water absorption produces a real increase in its frictional resistance. However, this does not necessarily mean that any hypothesized increase in leather slip resistance due to absorption will be significant for pedestrian safety in everyday ambulation. Slip resistance involves many considerations. For example, there may be too much water present on the walkway surfaces for its lubricating effects to be overcome by softened leather.

Care should be taken when choosing test-foot materials to include possible effects of water-absorption softening in wet-testing data interpretation.

It appears that in some circumstances, tribometers of the horizontal pull type, fitted with leather test feet, could experience significant surface-tension adhesion. Nevertheless, reinterpretation of wet-leather and other test-foot test results as an indication of the presence of sticktion appears appropriate. This includes the need to differentiate between real increases in frictional resistance arising from water-absorption softening and the presence of surface-tension adhesion.

The classical metallic friction expression, $\mu = F_T/F_N$, is valid only when the frictional contribution from roughness may be ignored as negligible.

It appears appropriate to identify and quantify frictional contributions from surface roughness when interpreting and applying slip-resistance test results.

It is probable that, as in metals, dry adhesion between contacting surface atoms in test feet and test surfaces makes a significant frictional contribution in slip-resistance tribometry.

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WALKWAY-SAFETY STANDARDS DEVELOPMENT

Ann E. Fendley [1]

What is Needed to Gain Valid Consensus for Slip Resistance Standards

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Reference: Fendley, A. E., "**What is Needed to Gain Valid Consensus for Slip Resistance Standards,**" *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424,* M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: ASTM and the various stakeholders in ASTM F13 Committee on Safety and Traction for Footwear hold widely differing philosophical positions with regard to friction safety standards, but have a common ground in wanting to see a reduction in slip and fall accidents. Since no existing friction-testing device can evaluate every aspect of pedestrian friction, conflicts exist between the stakeholders as to the appropriate use of these devices and standards based upon them. To speed the passage of needed slip resistance standards, analysis of the basis of stakeholder positions and ways to accommodate these positions is required to gain more rapid consensus. This paper addresses specific interests of the shoe, flooring and steel industries, producers of proprietary slip-testing equipment, consumers of footwear, workers, architects and builders, expert witnesses and politicians, academic scientists and of ASTM, and mentions issues that have prevented the timely passage of standards. It explores possible solutions to these conflicts, including the eventual replacement of proprietary-based standards with performance-based standards, and the inclusion in standards of statements relating to the limitations of the methods and clear descriptions of the methodology and stage of precision and bias testing. It discusses directions for future research, and mentions useful approaches to slip resistance standards writing in Australia and New Zealand.

Keywords: consensus, slip-resistance standards

Introduction

The magnitude of the slip and fall problem has been reviewed by numerous authors, including Englander [*1*], and Leamon and Murphy [*2*]. With regard to slip and fall prevention, complex issues arise related to friction generated between footwear bottoms and walkway surfaces. Friction-related factors, as well as the proliferation of slip resistance testing devices and limits of their validity and reliability, are discussed in the literature [*3-9*].

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[1] Associate Professor of Internal Medicine, University of Arkansas for Medical Sciences, Area Health Education Center - Pine Bluff, 4010 Mulberry St., Pine Bluff, AR, U.S.A., 71603.

Equally as complex as issues of friction and tribometry, are questions concerning what types of friction-related standards are needed and what types of statements should be included in those standards [*10-11*]. Such difficult questions foster an appreciation for the consensus process, for the different philosophical positions of the stakeholders in ASTM F13 Committee on Safety and Traction for Footwear, and for the need to find better ways of reaching consensus in developing standards. No matter how stakeholders may disagree about the basis of friction safety standards, they have a common ground in wanting to see a reduction in slip and fall accidents. Thus it is crucial to find effective ways for stakeholders to work together towards the passage of valid safety standards that ideally do not compromise the legitimate interest of any stakeholder.

Limitations of Friction Testing

Arguably, friction testing is valuable, and despite limitations, friction-testing methods can ultimately improve pedestrian safety. Nevertheless, there is a problem with lack of perfection in each of the many ways pedestrian friction is measured. No existing friction-testing device -- not horizontal pull drag sleds, not stationary or portable articulated strut tribometers, not inclined strut devices, not any ramp test or even the force plate -- can evaluate all aspects of pedestrian friction, nor predict when slips will occur. When we walk, our feet are not dragged along the walkway surface like a horizontal pull tribometer, and our forward leg is not a stiff rod like an articulated or inclinable strut. Our shoe bottoms are not composed of standard leather or other smooth substances often used to surface the test feet of tribometers, but rather they are made of a multitude of materials having various tread designs that modify traction and dispel contaminants. Our heels do not always contact the floor at a predetermined angle. Our shoes and floors are subject to wear that is not easily taken into account by standard tests. Even the most sophisticated whole shoe tester can not encompass the variability inherent in walking by persons of different ages, anatomical make-ups and abilities. Tests of human subjects walking on a force plate are subject to artifacts and, in addition, the time region where slip is likely to occur is rather difficult to capture. Ramp tests in no way mimic normal walking: we do not walk forward and backward in shortened steps on variably inclining planes with harnesses on our backs or holding onto railings. Finally, there is noise, inherent variability, of and between floor and shoe bottom materials. In short, what a friction test does is give us a rather noisy estimate of the relative traction developed between different combinations of materials under the specific conditions tested, in the presence or absence of contaminants. Tribometers of different design measure different 'aspects' of friction, which is a systemic rather than solely a material property. As a result, different tribometers give different values for slip resistance or coefficient of friction. In addition, because of the variability inherent in the floor and shoe-bottom materials, there is always some variability in the results, certainly between different types of machines, often between different machines of the same type, and sometimes with the same machine on different occasions.

Partly because of the above-mentioned limitations, no friction test can ever guarantee that a person will or will not slip in any given instance. That slipping is a low-probability event is an additional obstacle to guaranteeing that a person will or will not slip. Caution must be exercised in inferring from limited testing that a person who did slip did so because of the footwear or flooring. Nevertheless, if interpreted correctly and cautiously, friction testing can be of great value in protecting the safety of individuals, identifying problems, and giving us an understanding of which combinations of shoe bottoms and walkway surfaces tend to give better traction in specific situations.

Philosophical Positions of Stakeholders

The differing positions held by the stakeholders on the F13 Committee are readily understood.

The flooring, shoe and construction-materials industries provide us with an amazing array of attractive and useful products that make all of our lives better. Manufacturers may be concerned about the potential for lawsuits based on standards for equipment that does not represent the way people actually walk, and on standards that contain precision and bias statements that do not state exactly how the data was obtained.

Consumers of footwear want to retain the choice between fashion-conscious imported shoes with shoe bottoms that may provide little traction and shoes that are more safety-conscious with regard to friction. At the same time they will profit from more information as to which shoes provide adequate traction in defined situations.

Iron- and other construction-workers at risk of falling at construction sites, as well as warehouse, dock, and other workers exposed to oily or wet walkways are concerned for their own safety. They want slip-resistance standards to prevent fatal or serious-injury accidents.

Producers of slip-testing equipment are concerned with marketing their devices. They seek to promote the sale of their products, and to diminish the sale of competing products.

Expert witnesses in lawsuits want clear-cut friction guidelines in relation to safety. They want standard test methods for friction so as to meet criteria that allow them to testify.

Research scientists want scientific principles strictly adhered to in the development of standards. They question the validity of measurements and the definition of conditions in which measurements must be carried out. They insist on the appropriate application of statistical methods in evaluating friction data.

Politicians are under pressure from the workplace. They demand the rapid development of friction standards, the ramifications of which may not be adequately thought out.

ASTM wants to see that the consensus process is maintained, to assure fair representation of stakeholders, and to aid in the resolution of potential conflicts in the area of slip resistance. It wants to avoid litigation. It seeks to maintain its well-deserved reputation as a leader in the production of quality consensus standards, and to maintain good relations with other recognized standards-making bodies such as ANSI and ISO. To meet these ends, it is working towards the elimination of proprietary standards (those based on equipment produced by a particular manufacturer) and towards the development of performance based standards for slip resistance. As will be explained, the goal of performance based standards is to incorporate a framework of reproducible walkway surface and shoe bottom materials that can be used for friction testing with various equipment. Through research, results can be related to friction safety thresholds for actual human activities derived from biomechanical data.

Past Conflicts

Getting slip resistance standards passed in ASTM Committees, including F13 Committee on Safety and Traction for Footwear, has understandably been difficult. Differing philosophical views among the stakeholders have generated disagreements between individual members of committees and sometimes between committees, slowing the standards-making process. The Board of Directors of ASTM has now formed a special task group, the so-called "BOD Task Group" to assist stakeholders in slip resistance in working together toward the timely passage of meaningful friction standards.

Ways of Working toward a Solution

A goal of the consensus process in ASTM is to assure fair representation of the interests of each of the stakeholders on its various committees – whether they be industry, consumers, producers of slip-testing equipment, architects and builders, scientists or politicians. It is conceivable that this can be accomplished in several ways. First, more attention can be paid to a clear statement within our standards of the limitations of our methods, so as to limit their possible use as weapons for litigation against companies or ASTM. Second, clearer descriptions can be employed of the methodology of precision and bias testing. In this way, if issues are brought to suit, the parties in litigation can take a hard look at the real significance of the standard in question and its precision and bias testing. And third, performance standards for slip resistance tests can eventually replace proprietary standards to eliminate disagreements within the organization between manufacturers of proprietary equipment, as well as possible accusations of "restraint of trade."

Clear Statements of the Limitations of our Methods

Given that we can never have perfect methods or perfect precision, the best way to continue to gain approval by industry of high quality and workable standards is not only to make clear within each standard its significance and intent, but even more importantly to make clear how the method does or does not relate to pedestrian safety. The increased use of disclaimers within standards will allow industries and standards-making organizations to protect themselves in courts of law, and at the same time keep our workers safe. A lesson can be learned from the recent Standards Australia standard: Slip resistance classification of new pedestrian surface materials, (AS/NZS 4586:1999) adopted in 1999 in Australia and New Zealand. Quoting from the Scope, we see what the standard *does* do:

> *This standard provides a means of classifying pedestrian surface materials according to their frictional characteristics when determined in accordance with the test methods set out in Appendices A, B, C, and D. These test methods enable characteristics of surface materials to be determined under either wet or dry conditions.*

Quoting from the Application, we see what the standard *does not* do:

> *The indication of the test apparatus relates to the slip resistance potential of the surface in the test environment. It does not contemplate shoe sole materials, characteristics of individual gaits, or other factors that may contribute to slips.*

Another valuable approach used in Australia is the use of the handbook, An Introductory Guide to the Slip Resistance of Pedestrian Surface Materials (HB 197:1999), published by Standards Australia and CSIRO, to assist in the use of AS/NZS 4586:1999. The handbook discusses the philosophy of AS/NZS 4586:1999, that rejects the concept of a universal minimum slip resistance threshold value that is both practical and safe. Quoting from the Background:

> *In equating safety with coefficient of friction, one has to consider all the relevant variables, as well as whether the result has been unduly influenced by the method of slip resistance measurement. The slip potential is a function of footwear, activities, gait, contamination, environment and other factors.*

The document frankly discusses the appropriate use and limitations of various methods of slip resistance testing.

Clearer Descriptions of the Method of Precision and Bias Testing

Each standard method should contain a clear description of how the precision and bias was done. Precision and bias testing is logically done in stages. Standards may be put to use with precision and bias testing that does not yet meet ASTM Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method (E691). Nevertheless, the extent and nature of the testing should be made clear either in the standard or in an appendix.

Performance Based Standards; Efforts of the Board Task Group

The goal of the ASTM Board Task Group on Slip Resistance Standards is to coordinate the development of performance based test methods for slip resistance that include portable equipment and, eventually, biomechanical methods. It is in the interests of ASTM, and in the interests of safety ultimately to get away from the use of standards for proprietary apparatus and certainly to get away from the idea of defining a universal numerical safety threshold for slip resistance. First of all, different tribometer types can get different readings for the same pair of shoe bottom and walkway surface materials, depending on their design and the aspects of friction that they measure. Secondly, different activities will have different friction requirements. Slow walking will require less friction than fast walking or running. Turning, load carrying, ascending and descending stairs, and dancing will all have different friction requirements.

The recommended approach of the Board task group will likely be to establish sets of reproducible reference shoe and floor materials. These reference sets will have good repeatability characteristics and will represent an appropriate range of slipperiness covering the friction requirements of pertinent activities. With these reference pairs, a system is devised to plot a curve of slip resistance measurements against which the results of various slip-testing machines using shoe-surrogate materials as test feet can be verified. Then a *Standard Practice for Making Slip Resistance Measurements in the Field* can be created for use by the verified slip testing machines. It would be up to the manufacturers of the various slip testing equipment, not ASTM committees, to demonstrate the precision and bias of their equipment within this framework. The Traction and Research Subcommittees of F-13 are currently dealing with identifying suitable reference shoe bottoms and walkway surface materials for this effort. The Biomechanics and Footwear Construction Subcommittee has a Biofidelity task group that will define how the friction requirements of various activities are to be studied after reviewing relevant research. To this end, various modalities are appropriate to establish activity related friction requirements, such as force plates measurements and assessments of persons with specified shoe bottoms traversing walkways of specified materials. Once such friction requirements are determined, despite differing numerical results that may be obtained by tribometers of different designs for any given pair of reference materials, each machine's performance can be objectively related to required friction safety thresholds for actual human activities derived from biomechanical data.

Conclusion

In summary, the timely passage of valid consensus standards for slip resistance is vital to workers and to consumers of footwear and walkway surfaces. Clearer statements of the limitations of our methods in the form of disclaimers within standards, as well as clearer descriptions of precision and bias testing methods will allow industrial stakeholders to vote in favor of standards by protecting against unwarranted litigation. The development of performance based standards over proprietary standards will have the advantage of allowing the marketplace to decide which friction-testing device is superior. Performance based standards will also encourage manufacturers of slip-testing equipment to improve their devices, thereby promoting the common goal of reducing walkway accidents.

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Mark I. Marpet[1]

Issues in the Development of Modern Walkway-Safety Tribometry Standards: Required Friction, Contextualization of Test Results, and Non-Proprietary Standards

Reference: Marpet, M. I., **"Issues in the Development of Modern Walkway-Safety Tribometry Standards: Required Friction, Contextualization of Test Results, and Non-Proprietary Standards,"** *Metrology of Pedestrian Locomotion and Slip Resistance, ASTM STP 1424,* M. I. Marpet and M. A. Sapienza, Eds., ASTM International, West Conshohocken, PA, 2002.

Abstract: Walkway-safety tribometry standards need improvements in the area of machine neutrality and in more meaningful contextualization of test results. One of the underlying difficulties in improving these standards is that obsolete and incorrect abstractions of real-world resilient-surface friction underpin existing standards. Problematic abstractions include the static/dynamic friction model, the notion that the underlying friction model is deterministic, and the single-numeric-threshold method for determining whether or not a walkway surface, shoe bottom, or a combination of both, is or is not slip resistant. Significant improvements may be realized by considering required friction in the setting of slip-resistance thresholds and by a non-numeric ranking method for classifying slip resistance. The ASTM Board of Directors F13 Task Group recommendations for a new slip-resistance-testing model are seen to be both closely related to and congruent with the directions for improvement expressed in this paper.

Keywords: pedestrian safety; slip resistance; slip, trip, and fall accidents; tribometry standards; walkway safety.

Introduction: The Need for Walkway-Safety Standards

Fall accidents are the second largest generator of unintentional-injury costs, behind automobile accidents, and the highest generator of accidental fatalities among senior citizens[1]. Fall accidents are the second-largest generator of workplace accidents [2]. A significant share, if not the lion's share, of fall injury is precipitated by slips [3], where one foot (or both feet), encountering a low-friction regime, suddenly finds itself (or find themselves) beyond the body's 'center of mass.' A very wide range of factors determine the slip-resistance situation confronting the pedestrian. These include:

[1] Professor, Department of Computer Information Systems and Decision Science, The Peter J. Tobin College of Business at St. John's University, 300 Howard Avenue, Staten Island, NY 10301, marpetm@stjohns.edu.

(1) The floor surface, which can range from broom-finished concrete or toothed-metal gratings at the slip-resistant extreme to ice or a smooth, soapy, wet floor at the other.
(2) Shoe bottoms, which can range from aggressively treaded, inherently slip-resistant rubber formulations at the slip-resistant extreme to smooth leather, polyethylene, or hard nylon at the other.
(3) Contaminants, things that lie between the walkway and the shoe bottom, which can range from none to dust, hair, water, oil, tomato paste, and so on *ad infinitum.*
(4) The physical condition of the pedestrian, which can range from an athlete with a powerful musculo-skeletal system, quick reflexes and subtle balance to the mobility-impaired individual, who may be substantially lacking one in or more of the aforementioned areas, to pedestrians who ambulate only with the use of walkers, canes, crutches, or wheelchairs.
(5) The activity of the pedestrian, ranging from carefully walking to dancing, climbing stairs, pulling a load, jogging, or sprinting.

To minimize the toll that fall accidents take, it is desirable to be able to characterize in a valid and repeatable way, the slip resistance of the individual components making up the pedestrian/walkway interface, as well as any given set of interface components acting in concert. The field of study that seeks to accomplish this goal is called walkway-safety tribometry, whose practitioners have usually concentrated on isolating the contribution of a single factor, e.g., the effect of a given floor surface, shoe bottom, or a contaminant, upon the slip resistance picture. To accomplish that, the test-foot or -surface material under study is usually tested against a tribometric reference material. The coefficient of friction value obtained (some call this a slip-resistance coefficient, rather than a coefficient of friction) then must be contextualized, *i.e.,* the tribometric-test results must be tied to an analogous real-world situation.

This contextualization, defining the relationship of a tribometric-test result to a real-world situation, has not been well explored. All examples related to pedestrian safety that appear in standards and regulations relate the tribometric test to the real world by comparing the sample mean of a set of tribometric test results against a single numeric-threshold value:

(1) ASTM Standard Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine (D-2047) asserts an in-the-bottle acceptance threshold of 0.5 or greater for liquid polishes based upon the average of a set of readings from a carefully defined James-Tribometer-based test procedure.
(2) The Americans with Disabilities Act Accessibility Guidelines [4] contained a recommendation, ultimately withdrawn, that handicapped-accessible routes have a minimum friction of 0.6 on level surfaces and 0.8 on ramps. (The recommendation was withdrawn when it became clear that the tribometric underpinnings for the rule were deficient. [5,6])
(3) The American National Standards Institute Standard for Provision of Slip Resistance on Walking and Working Surfaces (ANSI A1264.2) recommends a threshold of 0.5 separating slip-resistant from not-slip resistant workplace walking and working surfaces.

None of these standards or regulations comes remotely close to forming or encapsulating a universal method for characterizing and contextualizing friction. What makes the measurement of pedestrian/walkway friction challenging, what makes the contextualization of friction-test results difficult, is that the reality of real-world friction is complex—far, far more complex—than its textbook idealization.

Friction: Reality vs. the College Textbook

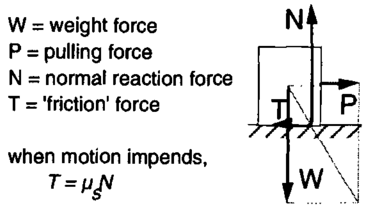

Figure 1 – *The 'textbook' definition of static friction.*

We can become prisoners of the abstractions that we use to help us make sense of the world around us. This is because our abstractions shape the very way we conceptualize and solve real-world problems. As our abstractions become more realistic, we often look back at the earlier rationalizations of empirical reality with we-know-better smugness. One does not have to think hard to come up with examples: an early and incorrect abstraction of the earth was that it was flat and located at the center of the universe. Such an abstraction literally did hold man prisoner; sailors needed to keep from straying 'too far' lest their ship fall of the edge of the earth. It is worth noting that an incorrect abstraction can make the analysis of empirical observations far more complex. For well over a thousand years, Ptolemy's geocentric flat-earth abstraction led mathematicians and astronomers into an extremely complex, make-believe world filled with the epicyclic motions of celestial bodies—the bobbing and weaving of the planets—to compensate for the incorrect held-as-'fact' abstraction that the earth, rather than the sun, was at the center of our solar system.

We are here interested in friction, that contact-based, dissipative force that resists relative motion. College physics textbooks (See Sears and Zemansky [7], for example) have almost universally adopted a modified version of the centuries-old Amontons-Coulomb [8, 9] model of frictional behavior. In the Amontons-Coulomb abstraction, friction is assumed to be solely a material property, and thus independent of contact time between the surfaces, area of contact, pressure, velocity and, significantly, of the measuring system itself.

The Static-Friction/Dynamic-Friction Abstraction.

The modification of the Amontons-Coulomb friction model mentioned just above is that the modern textbook abstraction of friction allows for two friction coefficients: *static* and *dynamic*. The static-friction force is the force in the plane of and parallel to the interface between two stationary bodies at the instant the motion of one body impends relative to the other. Dynamic friction is that force in the plane of and parallel to the interface between two bodies incurred during constant-velocity motion (in the direction directly resisting that motion). It is important to understand that static and dynamic friction are not of reality; they are make-believe concepts that were developed to help us make sense of the empirical. To a large extent, as long as the friction situation is simple, *e.g.*, non-resilient surfaces and the questions are easy, *e.g.*, concerning time-averaged friction coefficients, the abstraction works marvelously. At the same time, the static-friction/dynamic-friction abstraction holds some researchers and engineers in its thrall. The textbook model asserts that static friction is always higher than dynamic friction. D. James [10] empirically studied the behavior of the kinds of materials used in shoe bottoms: he found that the materials studied exhibited pressure and velocity sensitivity, and that it was not necessarily the case that the static coefficient of friction was greater than the dynamic. In spite of this, it is a common argument amongst walkway-safety professionals that [(pick one) static friction, dynamic friction] is a better measure of slip propensity than the other. If one is stuck in the static-friction-is-[(pick one) more, less]-important-than-dynamic mode, one will necessarily miss the fact that one thing material scientists can do to help prevent pedestrian slips is to develop materials that have increasing friction with increasing velocity, as suggested by James. Strict reliance by walkway-safety practitioners on the static/dynamic friction abstraction would be understandable if D. James' research were new, but it was published in 1980, time enough to allow the results to percolate through the walkway-safety community.

The Perfect-Test abstraction

Another abstraction that holds many walkway-safety professionals in its sway is that there is out there somewhere a single value that can encapsulate all the needed information about the slip resistance inherent in a shoe bottom, a walkway surface, or a set of interface materials. All a researcher has to do, the prisoners of that abstraction argue, is determine that single value with sufficient accuracy. The problem with why tribometer A gives different readings from tribometer B is reduced to which tribometer is more 'accurate,' which leads to cliques of self-interested parties engaging in efforts to prove their tribometer superior, forgetting to ask *why* the different tribometers are producing divergent results.

One important reason that different classes of tribometric instruments produce divergent results is that friction-test results are a function not *only* of material properties, as the Amontons-Coulomb abstraction postulates, friction is also a property of the device used to measure the friction, *i.e.,* a property of the measuring system. Each different tribometric-instrument—because of different contact areas, different pressures (Marpet and Brungraber [11]), different actuation velocities, and so forth (and for some instruments, unfortunately, for different operators of the same instrument)—can be *expected* to produce different results. Thus, arguing which tribometer is superior is meaningless unless one is willing to accomplish the research that ties the tribometers to the biomechanical properties of ambulation. (See Lanshammer and Strandberg [12] and Proctor and Coleman [13].) To date, this simply has not been accomplished. Another (preliminary) question to be answered is exactly what are the differences between tribometers. Some initial work has been accomplished in this area (Marpet [14], Marpet and Fleisher [15]).

Another facet of this 'single-value-as-the-truth' abstraction is the notion that the values obtained from tribometric-test results will, if testing is perfectly accomplished, be perfectly repeatable, and that variations from perfect consistency are due to error, to operator inconsistencies, improper preparation, and so forth. In many cases, that may be partially correct, but clearly, some, if not all, of the test-to-test variation may be due to the inherent noisiness of tribometric-test data. In other words, even if one were able to perfectly control each and every parameter and variable in testing, one would still not be able to produce deterministic-looking results; the best that one could hope for would be for the results to have perfect statistical consistency, which sounds like an oxymoron, but is not. Surfaces vary from day to day, with wear, temperature, etc. Some variation may be due to patterns that the testing is not sensitive enough to bring to the fore. Murphy [16] found, for example, that the slip-resistance coefficient distribution on a fast-food-restaurant floor followed a systematic pattern, with the most slippery area right in front of the deep fryers. Anyone that went onto that restaurant on that same day and ran a set of tribometric tests at *arbitrarily* selected locations would find that the results were noisy because the pattern that Murphy discerned through systematic (and very, very tedious) testing would not have become apparent. That said, it is clear that tribometric testing must be accomplished with a high degree of uniformity, as seemingly insignificant things can have a significant effect of the test results (See Fendley, *et al.* [17]). One guide to standardizing testing protocols is the ASTM Standard Guide for Measuring and Reporting Friction Coefficients (G115-98 from Committee G-02 on Wear and Erosion).

The Single-Numeric-Threshold Abstraction

Another place that our abstractions hold us in sway is in the contextualization of tribometric-test results: the relating of the results to real-world events, decisions, and factor-and-cause analysis. Currently, the common abstraction used to classify a walkway surface, shoe bottom, or interface set as slip resistant or not slip resistant is by thresholding, *viz.*, the comparison of the sample mean of a set of test results against a single, numeric value, called the *threshold.* A surface is characterized as slip resistant if the experimentally determined friction-coefficient mean falls above the numeric threshold, and not slip resistant if it does not. This abstraction is underpinned by the idea that a single value —the threshold value—can encapsulate all that there is that is significant in slip-resistance contextualization. One element, obvious to those with appropriate statistical background, is that this single number paradigm cannot possibly characterize the variability, the noise, inherent in tribometric testing. Another element, more subtle, to be sure, concerns the fact that the chance of a slip is a continuous, probabilistic function of the interface friction. It is not as if, assuming a threshold of, say, 0.6,

$$p(slip) = \begin{cases} 1; & \mu < 0.6 \\ 0; & \mu \geq 0.6. \end{cases}$$

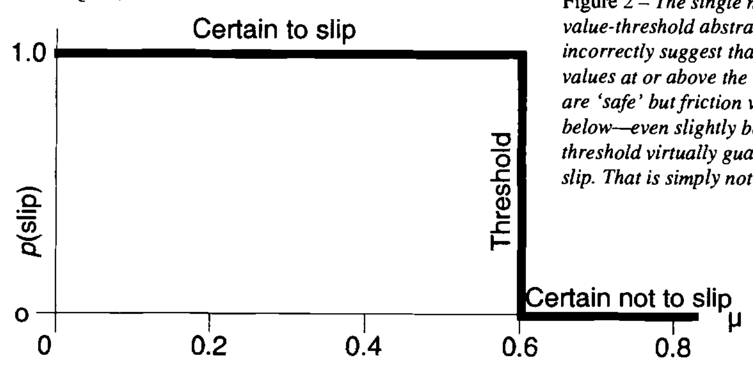

Figure 2 – *The single numeric-value-threshold abstraction can incorrectly suggest that friction values at or above the threshold are 'safe' but friction values below—even slightly below—the threshold virtually guarantee a slip. That is simply not the case.*

Rather, the relationship looks roughly like this (not to scale):

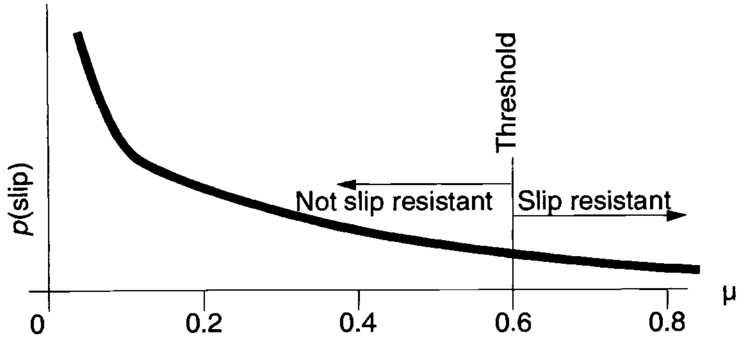

Figure 3 – *A single-value numeric threshold is superposed on a continuous probability distribution, here, the probability of slipping: P(slip). The threshold abstraction produces a decision picture that fails to take account of the continuous, non-singular nature of the friction/P(slip) relationship.*

Two things are worth noting. First, nothing sudden occurs at the threshold. Like a 55 mile-per-hour speed limit, one does not lose control the instant one ventures to 55.1 mile per hour. Secondly, the threshold value, like so many speed limits, has in the past been set as a product of negotiation, of administrative simplification, rather than set to minimize the aggregate systemic costs over the long term or, for that matter, to implement any other explicitly stated rational objective function.

Contextualization Alternatives

Let us briefly list other, possibly better, ways of relating friction-test results to the real-world.

(1) Because slips typically occur at low friction levels, one can define a threshold to be compared with the x^{th} percentile friction value (Marpet [18]), rather than compared with the sample mean. In other words, instead of comparing the average of a set of test values to a given threshold, say 0.5, the tenth percentile, called $x_{10\%}$, of the tribometric data set could be compared with a (lower) threshold. For example, let us say that 50 friction-test readings were taken, and the tenth percentile of the set of tribometric-result set was calculated. For a surface to be considered slip resistant, that tenth percentile value would have to exceed a lower-than-based-on-the-average threshold, say 0.4.

(2) Histogrammatic characterization requires that multiple percentile-based friction targets must be met. (Marpet, *ibid.*) Using the same example as above, one can require that, for a surface, shoe bottom, or walkway-interface set to be considered slip resistant, the x^{th} percentile friction value of the tribometric dataset must exceed a and the y^{th} percentile friction value must exceed b. For example, one might require the 25th percentile value of the dataset to exceed 0.45 and the second percentile value to exceed 0.35. By using histogrammatic characterization, fine control can be maintained at the left tail of the friction

frequency distribution, the place in probability space where slips, figuratively speaking, are most likely to occur.

(3) Leamon and Son [19], Leamon and Li [20,21] Leamon [22], and Myung, et al. [23] point to a slip criterion based upon the length of slip of a test foot. Although no tribometric instruments exist that work on that principle, such a tribometer is certainly possible, depositing the test foot on the test surface at a standard velocity and measuring the travel distance that the foot takes to decelerate to a stop.

(4) One does not have to quantify tribometric test results to make them meaningful. Say, for example, that one was attempting to determine if floor surface X, the to-be-tested surface, was slip resistant. One could hunt around and find a floor surface (call it R, the reference surface) that was generally agreed to be slip resistant, but just so. In other words, if surface R had been just *slightly* more slippery, we would not consider it to be slip resistant. Using any appropriate tribometer, one tests to see if surface X has a higher or lower friction coefficient than surface R. If X's friction coefficient is the same or higher than R's, Surface X is considered to be slip resistant. If X's friction coefficient tests lower than R, then surface X is not considered slip resistant. X's friction is determined with respect to R's, and not with respect to a numeric threshold. One could test the friction of surface X with different tribometers, all presumably using the same test-foot material. Assuming that X was truly slip resistant with respect to R, *i.e.*, ($\mu_X \geq \mu_R$), any tribometer that showed $\mu_X \geq \mu_R$ would give comparable results with respect to ranking the two materials. It would not matter if tribometer I determined that

$$\mu_X = 0.78 \text{ and } \mu_R = 0.65,$$

whereas tribometer II determined that

$$\mu_X = 0.58 \text{ and } \mu_R = 0.42,$$

the results would be rank comparable. This solves certain problems. First, as described just above, it solves the problem of comparability between the results of different tribometers. Secondly, this method solves, at least partially, the problem of temporal drift: tribometric-test results varying because the tests were conducted at different times. By taking the reference surface to the site of the testing, and testing the reference surface and the test surface contemporaneously, the rank of the tested surface to the reference surface should not suffer from drift problems. Of course, one must pick a reference surface that will itself be stable over time for this method to work.

Because a ranking system does not depend upon the numeric values determined in the test, only how those numeric results compare with results from the reference surface, the question of interpreting the meaning of the different numbers or differences in the numbers disappears. So does the problem of comparing the results generated by different tribometric instruments. This is very significant. Because one cannot expect one type of tribometric instrument to give numeric results comparable another type, *e.g.*, one cannot expect a James Tribometer to generate test results that will numerically correlate well with the results of tests conducted using a PIAST, there exists a potential for marketplace confusion. Ranking methods, because they are machine neutral, should eliminate that potential.

(5) Ranking is extensible. Not only can one test surface X against a single reference surface (Surface R, above), one can test the to-be-tested surface against a suite of reference surfaces, ranging from quite slippery to quite slip resistant. One can then characterize the slip resistance of surface X as to where it falls in the hierarchy of reference surfaces. Say that we have a set of k reference surfaces R_1, R_2, R_3, ..., R_k. R_1 is the least slip-resistant of the reference surfaces, R_k is the most slip resistant. If test surface X tested less slippery (more slip resistant) than reference surface R_2 but more slippery (less slip resistant) than surface R_3, we would rank-characterize surface X as, say, 2-3. This extension of the simple ranking method allows one to develop a test method that allows for different activity and use patterns. For example, it is clear that a person walking on a smooth floor in high heels has a different friction requirement than that same person, this time in work boots, pulling a heavy load across a concrete warehouse floor. The single-value-numeric-threshold model is an abstraction that seems to force its prisoners to take the position that only the available friction between the floor surface and the shoe bottom is relevant. In other words, the particular human activity involved in ambulatory activities is simply not a part of the walkway-safety paradigm: if the threshold is set at the 'correct value,' the single-value, numeric-threshold prisoner would argue, everything on the 'human side' will take care of itself. (To be fair, there is nothing inherent in the numeric-threshold model that *forces* reliance on a single value threshold. The fact is, however, there has been no support for a multiple numeric-threshold model in the walkway-safety community. Rather, fierce how-many-angels-fit-on-the-head-of-a-pin discussions focus on what single value best encapsulates the border between slip-resistant and not-slip-resistant surfaces. An extensive discussion of this can be found in Marpet. [24])

Ranking a to-be-tested surface against a reference-surface suite suffers from no human-side-of-the-picture limitation; one can use different reference surfaces to represent the friction required for different ambulation activities. So far, this paper has focused on only half the friction picture: the friction available between the floor and the shoe bottom. It is time to discuss briefly the other half: the friction required to perform a particular activity.

Required vs. Available Friction

The basic slip paradigm is that a pedestrian will not slip if the friction available between the floor and the shoe bottom: *the available friction,* is greater than or equal to the friction required by the ambulation activity: *the required friction.* Available friction is measured between floor and shoe-bottom surrogates using a tribometer. Required friction is measured by having human beings perform ambulatory activities upon an instrumented force-measuring plate (a force plate).

Different activities have different friction requirements. Straight-and-level, unhurried walking by an able-bodied pedestrian typically requires, for example, a friction level of $0.20 \leq \mu_R \leq 0.30$. Walking with crutches typically requires a friction level twice that (*op. cit.* D. James.) It is important to understand that each type of activity by each class of pedestrian (as a function of gender, age, health, presence of a mobility impairment, etc.) may require a different friction level. We can classify the various ambulatory activities as to their friction requirement. Here is an incomplete list, having very roughly increasing demand for friction:

1. walking on a known slippery surface,
2. careful walking,
3. dancing,
4. walking down a set of stairs,
5. walking up a set of stairs,
6. inside walking,
7. outside walking,
8. pushing a load,
9. carrying a load,
10. pulling a load,
11. walking using crutches,
12. walking down a ramp,
13. walking up a ramp, and
14. running.

To utilize required-friction information in assessing walkway safety, one needs first to assemble a complete list of human ambulatory activities, similar to the one above. Once this complete list is assembled, one needs to determine the friction requirements for each of the activities, understanding that the requirements vary as a function of the pedestrian and, especially, as a function of the use of walking aids.

Fortunately, much of this information, at least for able-bodied pedestrians, has been compiled in the walkway-safety-research literature. There is significant information concerning the frictional requirements for ordinary walking. One source frequently cited is Perkins, [25] which appeared in an earlier ASTM STP; see also Murray, *et al.* [26,27]. Ekkebus and Killey [28] present a simple analytical formulation of the required friction at walking heelstrike. Their analytical abstraction, simply put, is that the angle of large bones of the leg at heelstrike determines the required friction; this abstraction has been roundly criticized from a number of separate angles. (See Buczek [29] and Burnfield and Powers. [30].) Stair walking has been analyzed by Brungraber and Templar [31]. Empirical determinations of stair friction requirements have been published by Cristina, et al. [32] and by Powers, et al. [33]. Ramp walking has been covered in some detail by Redfern and DiPasquale [34] and McVey and Redfern [35]. Redfern and Andres [36] discuss the pushing and pulling of loads.

Walkway Safety Standards

The walkway-safety community has been working on the development of tribometric instruments for well over fifty years; two instruments developed in the 1940s, the James and Sigler tribometers, are still in use. In spite of this long gestation, it is clear that the tribometry standards and the formulation of acceptable practices still have a way to go, especially with respect to (a) contextualizing tribometric-test results and (b) having standards that are non-proprietary and performance based.

The Need for Thresholds

It would take it too far to suggest that contextualization of tribometric test results is not generally possible given the current state of development of walkway-safety-tribometry standards. A more realistic assessment is that such contextualization is more difficult than it should be, and many walkway-safety tribometry practitioners have neither the background, the understanding, or the sense of context to relate a tribometric result successfully to a real-world situation.

What one has to do to contextualize a tribometric result today is to:

(1) determine the foreseeable activities that are reasonably contemplated in a given environment;
(2) determine through literature search (or research) the required friction needed to perform these activities, to determine the required friction;
(3) select a tribometer that can reasonably analogize the friction situation under study;
(4) conduct tribometry testing, which characterizes the available friction;
(5) compare the required friction with the available friction.

What one too often observes is practitioners grasping on to any published threshold value whether or not it is relevant. It is, unfortunately, common for practitioners to assert that 0.5 should be the threshold between slip-resistant and not-slip-resistant surfaces in a field test, and point to ASTM Standard Test Method D-2047 (*op. cit.*). D-2047 is a test method that is designed and used to determine if a liquid floor polish, when properly applied, can be considered slip resistant. Not a field test, it is not capable of being used for a field test because the James tribometer is not designed to be used for field testing. None of this should suggest that Test Method D-2047 is flawed; the fact is, it has and does serve the important function of making sure that the polishes that are applied to floors will not create hazard if applied properly. Rather, the point here is that practitioners who lack the wherewithal to set a friction threshold will use D-2047 simply because it's out there.

Another anomalous behavior that one can observe is that practitioners will sometimes, here using 0.4 as a threshold for the sake of discussion, will play with the significant-digit count to prove or disprove that a floor or shoe bottom is or is not slippery. For example, if we determine that a floor under specified conditions tests out to be 0.386, practitioner A, wanting to prove slipperiness will round to two places (μ = 0.39), and declare the floor slippery. Practitioner B, wanting to prove the floor not slippery, rounds to one place (μ = 0.4) and declares the floor safe. Like the prisoners of Ptolomy's abstraction, who for centuries argued about why the planets did loop-de-loops, our single-numeric-threshold-value prisoners are reduced to arguing whether or not a floor is safe as a function of how many significant digits are significant!

There has to be a better way.

Non-Proprietary Standards

The Committee on Standards (COS) of ASTM, responsible for the integrity of the standards-development process itself, has sent down a mandate to ASTM Committee F13 on Safety and Traction for Footwear that requires that F13 develop standards in a manner that will minimize "marketplace confusion." The COS Committee was and is concerned about the possibility that a proliferation of proprietary standards would allow those who are trying to prove a point (rather than trying to objectively determine the safety status of a given walkway, shoe bottom, or interface) to 'shop' for a tribometer that will give them the results that they desire. To a certain extent, that happens now. Some, to cite an extreme example, ignore the written-into-the-standards limitation that drag-sled (the Horizontal Pull Slipmeter, for example) and articulated-strut tribometers (the James, for example) are not approved for wet-surface testing. Not interested in finding out whether the walkway is or is not slippery when wet, they utilize these tribometers because they *a priori* know that these tribometers will give high but scientifically meaningless results on wet surfaces.

F13 would go a long way towards eliminating marketplace confusion if it were to develop non-proprietary standards, *i.e.*, standards that do not reference any specific machine. In order to assist Committee F13 in that endeavor, the ASTM Board of Directors constituted a Task Group , chaired by the then incoming ASTM Chairman of the Board, with membership drawn from the officers of F13 and other interested parties, to explore the development of non-proprietary standards. That group has developed an outline, a skeleton, for the standard, and is presently in the process of developing answers to technical problems that have presented themselves in the course of development of the outline. When finished, it will be turned over to Committee F13 to flesh out a set of standards. The broad outlines of a machine-neutral, rank-based set of standards are presented below.

A possible future[2]

This last section of this paper is a work-in-progress. There are a number of standards that will have to be developed:

(1) A standard guide for the characterization of required friction as a function of various activities.
(2) A set of standard reference-material pairs, used to calibrate equipment and to classify the slip resistance of a shoe-bottom material or a surface being tested.
(3) A standard for the validation of tribometers.
(4) A standard test method for determining walkway/shoe-bottom slip resistance.
(5) A standard guide for conducting walkway-safety tribometer precision-and-bias determinations.

Addressing Required Friction in a Standard Guide

A standard guide for the characterization of required friction as a function of various activities, the first standard listed above, will take the practitioner from foreseeable

2 Much of this section of the paper was presented by the author at the November 15th, 2000, ASTM Committee G2 on Wear and Erosion Workshop on Friction Test Methods for Research and Applications.

activities to required friction levels. The development of this standard has been assigned to ASTM Subcommittee F13.20 on Biomechanics. Possible formats for the information in the Standard Guide are a friction line (analogous to a time line; see Figure 4) or a chart.

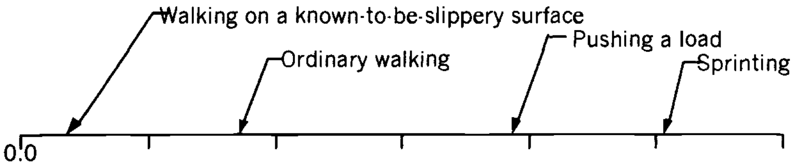

Figure 4 - *Required Friction Continuum*

Reference-Material Pairs

The next 'standard' to be considered is the set of standard reference materials. In general, a floor surface is tested against a test foot shod with a tribometric reference material. A shoe bottom is tested against a tribometric reference surface. In circumstances where both the floor surface and the shoe bottom can be controlled, tests may be conducted using the real-world materials as the test foot and test surface.

Tribometric test feet have in the past been surfaced with Standard Leather (D-2047), Neolite®[3] Test Liner (C-1028 and F-1679), or (in EC countries) RAPRA 4S tribometric-reference materials. Each of these materials has well-known problems:

(1) Standard leather does not come from standard cows. It is subject to the variability inherent in animal skin.
(2) Neolite® test liner is not a shoe-bottom material. It had originally been developed to test cobbler's adhesives. Questions have been raised about the quality control that goes into the making of Neolite® Test Liner [37].
(3) RAPRA products are rather expensive in the United States.

The shoe industry, through its representatives on F13, has made clear its desire to use materials actually used in shoe bottoms as tribometric test-foot reference materials. It is their position that the use of real-world shoe-bottom materials will make tribometric-test results inherently more credible. Presently, two materials, one a styrene-butadiene rubber (SBR) not unlike Neolite Test Liner and another of thermoplastic rubber (TPR) are being evaluated. *Ideally*, the composition of the reference-pair sets will consist of:

(1) A single test surface upon which a suite of different test-foot materials will be tested. Again, the different test-foot materials, which will range from *very* slippery to *very* tractive, will (hopefully) all have real-world shoe-bottom applications.
(2) A single test-foot material, under which a suite of different test surfaces, ranging between *very* slippery and *very* tractive, will be tested. Again, ideally, each of the tribometric test-surface reference materials will have real world application as a floor surface.

Besides clearly different friction values, ranging across the spectrum of interest, the reference materials should have the characteristic that, when tested, the rank-order of

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[3] Available from Smithers Scientific Services, 425 W. Market Street, Akron Ohio 44303.

friction values is generally preserved across different walkway-safety tribometers. This is essential for both tribometer verification and testing.

Verification-of-Tribometers Standard

It is clear that not every walkway-safety tribometer can perform tests under all conditions:

(1) There must be similarity between the friction model that underpins the required friction determination and the friction model that underpins the walkway-safety tribometer test.
(2) There must be verifiable faith in the rank-order process. That is, the rank-order process must behave consistently.

It has been discussed at length above that resilient-material-friction-test results are not only a material property, they are also a property of the measuring system. For example, slips on wet surfaces are generally precipitated by a hydrodynamic, squeeze-film phenomenon. The up-angled heel skidding on a film of water in a heel-strike slip is often analogized to the ski of a water skier skimming across the water's surface. Any tribometric test that attempts to capture that phenomenon must also be capable, running with the analogy, of water skiing, of reproducing the squeeze-film hydrodynamic friction model. (*op. cit.* Proctor and Coleman.) This implies that a drag sled (or an articulated-strut tribometer, which is nothing more than a drag sled with an automatic means of applying the lateral force) is unsuitable for wet-surface testing. Thus, one of the 'tribometric-conduct rules' that needs to be established is that, in general, the friction model used in the test must match the friction model of the phenomenon under study. In that light, drag sleds and their kin must not be used for wet-surface testing.

There must be verifiable faith in the rank-order process. The key to acceptable results is that the rank order of the reference-material-pairs set be preserved. That is, the material pairs will range from the most slippery to the most slip resistant and the walkway-safety tribometer test results will preserve the most-to-least-slippery order of the material pairs. The mathematical description of this characteristic is that the walkway-safety tribometer test results must be a monotonically increasing function of the reference-material-pairs slip-resistance rank order.

If a given walkway-safety tribometer cannot preserve the monotonically increasing rank-order of the slip-resistance measurements of the reference-material-pairs, that walkway-safety tribometer cannot be used to test materials in the area where the monotonicity is not preserved

The Standard Test Method for Determining the Rank of the Test-Subject Material

To accomplish a friction test, a walkway-safety tribometer, validated according to the criteria immediately above, shall be operated in conformance with the manufacturers instructions, to determine the rank of the test subject as follows. For the purpose of this discussion, let us assume that the test subject is a floor surface. At the test site, determine by tribometric testing slip resistance of the material pairs that would reasonably be expected to surround the test-surface's test-result reading. If this is not-at-all known, the operator might have to test the complete reference-material set. Record the results of these determinations. When that is complete, test the floor surface in question, using the same test foot that was used to test the reference-material pairs.

Based upon the test result obtained, rank the floor surface within the context of the reference-material test set. This has been discussed above.

A Standard Guide for Conducting Precision and Bias Studies

One of the most arduous and expensive tasks resulting from the fact that F13 entertains standards for proprietary equipment is that F13 finds itself responsible for the development of Precision and Bias Statements for those proprietary standards. With generic standards, Committee F13 would be freed from the responsibility of conducting tests on each and every walkway-safety tribometer that it writes a standard for. That should not suggest that the committee will be freed of precision-and-bias work. Far from it, but the scope and direction will certainly change. F13 will have to concentrate on (a) the repeatability of the reference-material pairs and (b) the precision of the ranking methods, with questions such as 'What is the possibility that a reference-material pair will test out of order, even if it is not?'

Pushing the development of Precision and Bias down to the walkway-safety tribometer manufacturer or to the walkway-safety tribometer user will be problematic unless those wishing to perform such analyses are given the proper tools.

The last standard proposed is a standard for conducting precision-and-bias determinations for walkway-safety tribometers, and for the reference materials used in walkway-safety tribometer testing. Precision-and-bias standards from ASTM Committee E11 on Statistics are generic Analysis-of-Variance and Analysis-of-Means tools tuned to look at between- and within-laboratory variation. In general, adapting an experimental design to a specific context generally simplifies both the experimental design and concomitant analysis.

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Richard Bowman,[1] Carl J. Strautins,[1] Peter Westgate,[1] and Geoff W. Quick[1]

Implications for the Development of Slip-Resistance Standards Arising from Rank Comparisons of Friction-Test Results Obtained Using Different Walkway-Safety Tribometers Under Various Conditions

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Abstract: This paper studies the extent to which different tribometers consistently rank the slip resistance of a series of different ceramic tiles, as measured by a number of techniques. An accelerated abrasion treatment was used to determine how the slip resistance might change with wear in service. It forms part of a wider study of the slip resistance of stone, concrete, vinyl, rubber and other pedestrian surfaces. Although most techniques ranked the tiles in a similar order, there were some notable exceptions. Underestimation or overestimation of available slip resistance may cause significant problems, whether in the evaluation of a new product or an existing walkway surface. It is important to determine when specific tribometers may give "incorrect" results on particular types of surfaces, in order that a more reliable assessment can be made. This may require the use of a different technique, a dissimilar test foot, or modified test procedures or parameters. When a hard rubber test foot was used, the slip resistance tended to reflect the altered surface roughness of the abraded tiles, but when a resilient rubber was used, there was a general increase in the slip resistance. These results confirm the complex interplay between surface topography and choice of test foot. The results also indicate that current commonly used test methods can yield results that poorly predict the traction available to a pedestrian, either when the product is new or after the surface wears. This study found that the manually-pulled 50-pound drag sled (as used in ASTM C-1028) was incapable of satisfactorily distinguishing between the wet slip resistance of ceramic tiles. The pendulum tribometer (used according to AS/NZS 4586, with TRRL rubber, similar to ASTM E-303) provided more reliable results than the English XL Variable Incidence Tribometer (used according to ASTM F-1679).

Keywords: slip resistance, tribometer, sustainable, ceramic tiles, coefficient of friction.

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[1] Principal Research Scientist, Research Student, Technical Officer and Experimental Scientist, respectively, Sustainable Slip Resistance Systems, CSIRO Manufacturing and Infrastructure Technology, Graham Road, Highett, Victoria 3190, Australia.

Introduction

Efforts to minimise slips and associated falls have been hampered by questions as to how to best measure the slip resistance of flooring materials and the interpretation of such data. Different walkway-safety tribometers, operating on a number of different principles, often give different results as an inherent function of the tribometer and, thus, may underestimate or overestimate the traction available to a pedestrian. Moreover, since the result also depends on the nature of the surfaces being measured (the walkway surface and the surrogate test foot), a tribometer might overestimate the available traction in some circumstances and underestimate it in others. This poses difficulties in establishing appropriate compliance criteria for the tribometer, let alone a generalised universal threshold for all test methods.

In 1991, an ASTM F-13 workshop at Bucknell University analysed the behaviour of four generic types of tribometers, where the tribometer readings were compared with the results generated on a force plate [1,2]. Of the nine tribometers tested, only the inclined strut (PIAST) and (Sigler) pendulum tribometers were found to be capable of modelling hydrodynamic phenomena due to a lack of significant residence time. They were thus considered capable of measuring wet-surface friction [2].

The coefficients of friction that are obtained by various tribometers can also be a function of the geometry and resilience of the surface being assessed. There are limitations in using a surrogate test foot (slider) to approximate the wide range of footwear in the marketplace, since the characteristics of the test foot material are certainly influential. Distinct devices (often using different soling materials) can thus indicate dissimilar levels of slip resistance (when all results are expressed as coefficients of friction). These considerations suggest that compliance criterion intended to provide an adequate pedestrian traction will necessarily vary from tribometer to tribometer.

If a study is conducted that suggests that a specific tribometer provides acceptable results on one or two specific surfaces, this does not assure that it is suitable for making measurements on distinctly different surfaces. One should thus consider that the inherent limitations of some tribometers might render them incapable of making meaningful measurements on specific types of surfaces, for example, using a drag-sled, where the vertical load is applied long before the horizontal force. Other tribometers may be unsuited to testing severely profiled, highly textured or extremely resilient surfaces. Because broad acceptance of this concept is a prerequisite to further significant advances, it is appropriate to review some past studies. Where the general acceptance of a device is based on studies that have been limited to a few surfaces that do not represent the full range of textures and roughness that are typically encountered, it would be appropriate to exercise some caution in extrapolating its suitability for use on other surfaces.

Studies of people walking over force plates [3–5] are generally accepted [1] as providing the most accurate assessment of pedestrian traction demand. While force plates instinctively provide the best basis for assessing the accuracy of a device on any specific surface, there is some discrepancy in the published literature as to the required or utilised friction.

Harper *et al.* [3] used a force plate to establish that the average coefficient of friction produced when walking in a straight direction was between 0.16 and 0.22 (124 subjects).

Perkins [4] found that the average required friction at touchdown was 0.22 (six subjects) with a maximum of 0.33. Buczek *et al.* [5] found that the mean required or utilised friction was 0.31 (± 0.07) for five able-bodied people, and 0.61 (± 0.26) for the affected side of five disabled people. Despite the small number of subjects, this study was used as the basis for the Americans with Disabilities Act requirements [6]. Although a much larger body of required-friction data has been generated in gait and biodynamics studies, it has rarely been explicitly published in the literature.

On the basis of the Building Research Station study [3], it was estimated that one person in a million would have a traction demand in excess of 0.4 for straight walking and turning corners. Pye [7] has since used the same raw data (for 87 men and 37 women, all fit and able and between the ages of 18 and 60) to publish Table 1. His risk analysis assumes that by statistical means the chance of a person exceeding a certain high coefficient of friction can be extended from a small population. Pye acknowledged that this was suspect. However, he opined that persons who walked in such a manner, so as to exceed regularly a coefficient of friction of 0.35, would often slip on wet floors, and learn to modify their gait so as to lower their traction demand.

Table 1 – *Relative risk associated with coefficients of friction between foot and floor (after Pye [7]).*

Risk	Walking straight	Turning: left foot	Turning: right foot
1 in 1 000 000	0.36	0.40	0.36
1 in 100 000	0.34	0.38	0.34
1 in 10 000	0.29	0.34	0.33
1 in 200	0.27	0.31	0.32
1 in 20	0.24	0.27	0.29

It should be anticipated that further larger studies will be conducted, where they also include a more representative population (including older people and persons with disabilities). If such studies indicate that the typical traction demand is 0.25 rather than 0.22 for the able bodied, the risk analysis will need to be recalculated. However, since one must not discriminate, it would be appropriate to conduct analyses for the whole population as well as its segments: the temporarily able bodied, those with functional limitations, and those with severe functional limitations.

The available traction is as much a function of the footwear and any contaminants present, as it is of the floor surface. In Europe, interlaboratory studies of the slip resistance of footwear were conducted where comparisons were made between test machines (based on force plates or load cells) and people walking (both on the level over force plates and on ramps) [8]. While the results were largely inconclusive because there was too little difference in the slip resistance of the footwear that was studied, the observed coefficients of friction depended on the technical test parameters of the test machines, e.g. vertical force, test speed, contact area and time of contact between the shoe and the floor. There were also some methodological problems relating to the use of test persons for assessing slip resistance. However, analysis of the German ramp-based test methods for determining the slip resistance of floors and shoes has shown that adequate test-subject training, standardization, and calibration improves the precision and limits the individual, test-person-dependent effects on the results [9]. English [10] has questioned the relevance of walking on a ramp to walking on the level, recognising that a natural gait pattern becomes different at high slopes. However, the intention is to reliably determine the available traction, rather than to replicate a walking-on-the-level gait. James [11] has explained that very short half-steps are used throughout such testing, because the coefficient of friction on a ramp is a function of the step length. Hence, a very short step is necessary in order to yield a measure of the available friction of the test surface when it is installed as a horizontal floor. The tangent of the critical ramp angle gives the available coefficient of friction of the tested shoe-bottom/floor-surface combination when used on a level floor.

The slip resistance of new products is primarily assessed to provide architects with design guidance. The German insurance system requires that new products have minimum levels of slip resistance, which vary according to the intended usage of commercial and industrial premises. The insurance companies and the trade unions, the two parties with the greatest vested interest in worker safety, determined these requirements and periodically review and amend them. For example, it is possible that the R9 classification may be withdrawn; the lower acceptance angle allows the inclusion of some products that are too slippery for some of the usage applications [12].

While the German system is otherwise eminently sensible, there is a fundamental limitation. The German slip resistance classifications are based on ramp tests that can only be conducted in the laboratory, and on samples that are a nominal 1.0×0.5 m in size. Thus other tribometers, capable of testing in the field, are required to determine how much the slip resistance of a floor changes due to wear or contamination.

Specifying a product that will initially have sufficient slip resistance is only a starting point to ensuring that a walkway surface will be suitably safe. Architects need to know how the slip resistance of floors may change in specific service conditions. However, the prevention of slips and falls may depend on several people once a walkway surface is installed. Insurance companies are increasingly expecting that the slip resistance of floors be regularly audited, and thus that property managers should be able to interpret slip resistance data. How relatively safe is the floor, and to what proportion of the population does it represent a significant risk? Do non-experts have sufficient knowledge to assess whether premature wear or inappropriate maintenance methods have compromised its safety? Should remedial action be taken and what options are appropriate in given circumstances? How well can the various tribometers determine changes in floor conditions? Would janitors and cleaning contractors require education and training in pedestrian friction and tribometry if they were required to ensure that they were providing an adequately slip-resistant surface? Is the tribometer that they might use capable of providing a reliable indication of how the slip resistance of the floor is changing? In order to fully answer such questions, much practical research remains to be performed.

The European Construction Products Directive 89/106/EC has established Essential Requirements that must be satisfied in order to minimise any health or safety risk to building occupants. This basically requires that products must provide adequate slip resistance at the end of their service life. This will presumably necessitate an accelerated wear conditioning protocol in order that likely future performance can be assessed.

ASTM International is presently undertaking a fundamentally different approach to creating a non-proprietary tribometric standard [13] that will compare the slip resistance of test specimens against sets of reference materials (which represent a continuum of slip resistance from low to high traction). It is expected that the walkway surface, shoe bottom, or combination of both that is being evaluated will be ranked in comparison to the reference-set materials, bypassing the numeric values obtained by a specific test method or instrument. Part of the qualification process that instruments are likely to have to undergo is an evaluation that would demonstrate it to be appropriate for measuring the specific set of test conditions, for instance: the nature of the walkway surface, the test foot and lubricant or contaminant. It is anticipated that the new standard will include pass/fail thresholds for different activities such as walking, running, pushing a heavy load, descending a ramp, etc. This should enable the establishment of classes of slip resistance that might be used in a similar way to the existing German classifications.

Unfortunately, contrary to what we might have learnt during high-school physics, polymers do not obey the classic laws of friction. It is thus important to have a better understanding of how the nature of polymeric soling materials might influence the test results. Pendulum-type tribometers operate based on the energy lost when a swinging spring-loaded test foot makes ground-contact over a specified travel distance. Andrew [14] used a modified form of the Pendulum, an Enhanced Laboratory Skid Tester (ELST), to study the energetics of transient contacts between polymers and inorganic substrates. When the ELST test foot swept over a surface, energy was dissipated by a number of mechanisms, some of which interact: reversible adhesion; disruptive adhesion; gross deformation; reversible micro-deformation; abrasive wear; mechanical alignment; and viscous drag. Perhaps the most important component in the energy loss was the wear of the test foot. Andrew also found that deposited films of test foot material on the test surface could strongly influence the observed coefficients of friction. Given the wide range and types of shoe soling materials, it is important to understand how the characteristics of the test foot can influence the measured coefficient of friction. This is fundamental to both the selection of appropriate test foot materials, and the interpretation (and extrapolation) of any test results that are obtained. Andrew [14] developed generalised energy loss equations for thermoplastics and elastomers, the two main types of polymeric soling materials.[2]

For a thermoplastic material, Andrew [14] could separate the frictional force into two separate components, a term due to adhesion and a term due to abrasive wear, by the use of experiments employing a combination of surface textures and lubricants. In lubricated sliding, the dominant frictional force for a thermoplastic appears to be abrasive wear. When dry, a rough test surface produces lower coefficients of friction

[2] *Thermoplastics* are often simply called plastics. They are capable of being repeatedly softened by heat and hardened by cooling. Polyvinylchloride (PVC), high-density polyethylene (HDPE) and nylons are typical of the thermoplastic family. *Elastomers* have a low density, crosslinked molecular structure. These rubber-like polymers can be stretched at room temperature under low stress to at least twice their length and recover their original length upon removal of the applied stress. When heated, elastomers degrade rather than melt. Natural rubber, nitrile rubber (acrylonitrile butadiene) and ethylene-vinyl-acetate copolymers (EVA) are typical elastomers.

than a similar smooth surface (since the rougher surface profile reduces the intimate area of contact between the thermoplastic test foot and the test surface, leading to a corresponding reduction in the contribution of adhesional forces). There may be a significant amount of abrasive friction on the rougher surface, but this contribution does not appear to be large enough to compensate for the reduction in the adhesion component. However, with lubrication this is reversed: rough test surfaces producing higher coefficients of friction (since lubrication greatly reduces the adhesion component).

In general, elastomers at room temperature exhibit far higher coefficients of friction than thermoplastics [14]. For elastomers on dry plate glass surfaces, adhesional forces dominated the friction force. An effective lubricant removes that adhesion component and therefore greatly reduces the friction force. On lubricated plate glass surfaces the friction force falls to almost zero due to the negligible contributions made by the deformation term. The friction force on a sandblasted surface was composed of a contribution due to both adhesion and deformation. When the elastomer was sliding over the dry sandblasted glass, the adhesion component was greatly reduced, while the deformation plus abrasive wear component had increased to be almost equal in magnitude to the adhesion. The elastomers tested all exhibited different magnitudes for both adhesion and deformation plus abrasive wear components [14].

James [15] has published dynamic-mechanical-thermal analysis traces of the TRRL and Four S rubbers.[3] The TRRL rubber has a very low tan δ[4] at room temperature, implying very little contribution to wet friction. In comparison, the Four S rubber has a higher elastic modulus that shows a steady decrease with temperature, and a higher tan δ at room temperature. It is thus more sensitive to low degrees of roughness than the TRRL rubber and, additionally, gives friction values that are relatively independent of velocity. James thus stated that on relatively smooth surfaces, the Four S rubber gives better discrimination than the TRRL rubber, whereas on rough pavements the reverse is true.

Flynn *et al.* [16] found that the 95% reproducibility[5] limit was 0.09, when six different Variable Incidence Tribometers (VITs) were used to test the same three smooth wet surfaces (float glass, vinyl tile and glazed ceramic tile). This means that a reading of 0.41 is not distinguishable from a reading of 0.50 or 0.32. Flynn and Underwood [17] also found that the 95% reproducibility limit was 0.09 and the 95% repeatability[6] limit

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[3] Both rubbers are produced by Rapra Technology Ltd, UK. The TRRL rubber was named after the Transport Road Research Laboratory. The term Four S represents Standard Simulated Shoe Sole.

[4] When an elastomer is vibrated, the stress and the strain are not in phase, and energy is lost as heat. The dissipation factor (tan δ), or energy loss, is measured using Dynamic Mechanical Thermal Analysis as the tangent of the phase angle between stress and strain.

[5] Reproducibility deals with the variability between single test results obtained in different laboratories, each of which has applied the test method to test specimens taken at random from a single quantity of homogeneous material prepared for an interlaboratory study.

[6] Repeatability concerns the variability between independent test results obtained within a single laboratory in the shortest practical period of time by a single operator with a specific set of test apparatus using test specimens taken at random from a single quantity of homogeneous material prepared for an interlaboratory study.

was 0.05, when six independent laboratories used their own VIT to test three types of ceramic tile under both wet and dry conditions.

Powers *et al.* [18] found that, when the VIT was used to test a dry smooth vinyl composition tile, it overestimated the peak coefficient of friction by 30%, when compared to healthy adults walking across the same surface on the same force plate at comparable impact angles. They believed that the differences in the measured utilised coefficients of friction were most likely related to the fact that the VIT test feet do not have the same vertical and horizontal accelerations of the pedestrian's lower leg at heel strike.

Our paper considers wet tests only, as we consider that dry tests on new walkway surfaces under uncontaminated situations represent an artificial situation that rarely occurs in the real world. Most slips on dry surfaces involve some form of residual contamination, dust or other dry contaminant. In the absence of any contaminant, some very smooth, flat, high gloss surfaces will yield very high results that imply that they will be safer than walkway surfaces that have been proven to be safe, e.g. brushed concrete. We contend that it is better to concentrate on using a standardised contaminant (e.g. water, oil, glycerol, or as is appropriate to the study) that can be consistently applied, to predict how potentially dangerous a surface may be under dry conditions if it becomes contaminated. Notwithstanding this, it can be very useful to obtain a measure of the difference between the available traction under ideal dry and wet conditions, as the likelihood of a slip will tend to increase as the magnitude of the difference increases. While such testing might be most effectively performed in field studies, laboratory trials might yield useful results, particularly if the condition of the walkway surface is appropriately modified to simulate anticipated wear or maintenance conditions.

Experimental Method

Materials

A range of Australian and imported tiles were used in this study. They had a nominal size of at least 300 x 300 mm. Six of the tiles (tiles A to F) were from the same batch of tiles that had been used in an interlaboratory pendulum study, where 26 laboratories took part. While it is difficult to precisely describe the surface characteristics of tiles, Table 2 attempts to do so. Typical R_z (once known as R_{tm}) surface roughness figures are given.

Tile H was treated with a proprietary floor surface etching treatment product, thereby creating tile J. This resulted in a slight loss of gloss. In a related investigation, four further levels of etching treatments were also made on tile H in order to determine the extent to which the changes, that were visibly evident, could be detected by the tribometers (these tiles are not shown in Table 2).

Some tiles were also tested after being subjected to various numbers of abrasion cycles, using ISO 10545.7 Methods of sampling and testing ceramic tiles: Determination of resistance to surface abrasion - glazed tiles. The size of the abraded area (80 mm diameter) restricts this slip resistance testing to the SATRA STM 603 and the VIT.

Table 2 – *Description of tiles and their R_z surface roughness.*

Tile	Description	R_Z, µm
A	Surface protected smooth porcelain	11.5
B	High gloss glazed tile with coarse particles penetrating above surface[1]	9.6
C	Matt glazed tile	16.8
D	Surface protected porcelain tile with spatterdash surface finish	19.5
E	Glazed tile with fine grit finish and lightly veined surface profile	28.3
F	Unglazed terracotta	20.7
G	Polished porcelain tile	8.4
H	Polished porcelain tile, after acid etching treatment	7.7
J	Porcelain tile with spatterdash surface finish	44.9
K	Porcelain tile with a series of pronounced ridges	33.3

[1] Decorated using engobe, glaze, fixative, dry glaze and cover coat applications. The dry glaze contained additions of 5% silica (18 to 40 mesh) and 15% alumina (100 mesh).

Test Methods

The wet slip resistance of the tiles was assessed using a number of tribometers and test methods, as summarised in Table 3. Testing with the VIT was done in accordance with ASTM Standard Test Method for Using a Variable Incidence Tribometer (VIT) F-1679-00, except that both 180 and 400 grit papers were used to prepare the test foot. The 400 grit paper was used to prepare the Pendulum and SATRA test feet. All ramp tests were conducted at CSIRO in a laboratory that is maintained at a nominal 23°C. The other tests were conducted in a laboratory at 23 ± 2°C and 50 ± 5% relative humidity. The wet barefoot and shod wet ramp tests were conducted with running water (6 L/min), where a small amount (1 g/L) of neutral wetting agent was added to potable water. The other tests were conducted using deionised water. R_z roughness was measured using a Surtronic 10 instrument, where the mean of 10 readings is reported.

Table 3 – *Summary of wet slip resistance test methods reported in this paper.*

	Test device	Method and specific conditions, where modified	
1	SATRA STM 103	SATRA TM 144	Four S rubber, 400 N load
2	SATRA STM 103	SATRA TM 144	Four S rubber, 100 N load
3	SATRA STM 103	SATRA TM 144	TRRL rubber, 400 N load
4	Pendulum	AS/NZS 4586	Four S rubber
5	Pendulum	AS/NZS 4586	TRRL rubber
6	English XL VIT	ASTM F-1679	Neolite® Test Liner
7	English XL VIT	ASTM F-1679	Four S rubber
8	English XL VIT	ASTM F-1679	TRRL rubber
9	Wet barefoot ramp	AS/NZS 4586	Bare feet, running water + wetting agent
10	Oil-wet ramp	AS/NZS 4586	Bottrop nitrile rubber boots, oil
11	Shod wet ramp	RAPRA CH0001[1]	Four S shoes, running water + wetting agent
12	Drag sled	ASTM C-1028	Neolite® Test Liner

[1] Rapra Procedure CH0001. Laboratory determination of the slip resistance of pedestrian flooring materials under water-wet conditions. Walking method – Ramp test. Shrewsbury, UK: Rapra Technology Ltd, 1997.

The SATRA STM 603 is a laboratory-based tribometer that is a commercial derivative of the equipment described by Perkins and Wilson [19]. It allows accurate control of four key parameters: applied vertical force, speed of moving of the test flooring surface, static contact time[7] and exact point at which the coefficient of friction is determined.[8] The machine is PC-controlled to ensure accuracy and repeatability, and has its own on-board computer and monitor screen. Pre-loaded software controls the data acquisition and logs the data during every test run. Each of the reported results is the mean of at least four tests, where a 25 mm wide section of the test rubber was mounted on a metal block and tested at a 5 degree angle to the tile surface. 400 grit abrasive paper was used to prepare the test feet. The speed used was 100 mm/s. There was a static delay of 0.2 s, and the dynamic coefficient of friction was determined 0.3 s after sliding commenced. The 0.2 s static delay time is an inherent element of the SATRA TM144 test procedure.

Giles *et al.* [20, 21] have described the development and performance of the Pendulum, as well as factors affecting the results, standardisation of instruments and their long-term accuracy. The Pendulum is used in a number of standards, for example, ASTM Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester (E 303-93),[9] as well as AS/NZS 4586:1999 Slip Resistance Classification of New Pedestrian Surface Materials. The results, obtained in BPN units, were then converted to coefficients of friction.

The ASTM Standard Test Method for Determining the Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method (C 1028-96) uses a 76 × 76 mm Neolite®-Test-Liner test foot and a 50-pound drag sled. Manually pulled drag sleds are widely considered unacceptable.[10]

Experimental Results

The experimental results are given in Tables 4 and 5, and Figures 1 to 10, where the results in Figures 2, 3 and 4 have been placed in the order of the TRRL pendulum results. Unless otherwise stated, as in Figures 9 and 10, the VIT results are those where 400 grit paper was used for test foot preparation. For ease of comparison, the ramp results, usually quoted as angles, have been converted to coefficients of friction by using the tangents of the angles.

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[7] The static contact time is the delay in time between the test foot coming into initial contact with the walkway specimen, and horizontal movement of the flooring relative to the test foot.

[8] The dynamic coefficient of friction is automatically calculated in terms of the average, peak and snapshot values. The snapshot value can be programmed to occur at a specific point or distance after sliding commences, by specifying a time, given the speed selected for that test.

[9] The precision and bias statement indicates that a sample size of 5 is needed in order to ensure that the testing error stays within 1.0 BPN unit at a 95% confidence limit.

[10] Manually operated horizontal pull testers permit the test foot to substantially reside on the surface before applying the test force. As such, they are not suitable for making wet slip resistance measurements of footwear or walkway surfaces. Furthermore, manually operated horizontal pull testers are technically inappropriate due to uncontrolled, non-uniform and non-normal application of force and rate of force application.

Table 4 – *Summary of experimental results, after conversion to coefficients of friction.*[1]

Tile[3]	Test method											
	1	2	3	4	5	6[2]	7[2]	8[2]	9	10	11	12
A	0.22	0.14	0.04	0.27	0.16	0.16	0.16	0.04	0.19	0.12	0.24	0.54
B	0.25	0.23	0.08	0.45	0.19	0.72	0.71	0.32	0.21	0.14	0.43	0.92
C	0.36	0.30	0.12	0.41	0.24	0.25	0.23	0.04	0.26	0.21	0.35	0.67
D	0.50	0.42	0.16	0.52	0.33	0.82	0.81	0.41	0.34	0.35	0.52	0.83
E	0.50	0.42	0.20	0.52	0.36	0.83	0.82	0.43	0.38	0.39	0.57	0.77
F	0.54	0.53	0.29	0.63	0.43	0.82	0.80	0.50	0.39	0.37	0.64	0.79
G	0.41	0.27	0.09	0.22	0.15	0.04	0.04	0.03	0.21	0.06	...	...
G_{1500}	0.48	...	0.20	...	...	0.05	0.05	0.03	...	...	...	...
G_{12000}	0.48	...	0.21	...	...	0.08	0.04	0.04	...	...	...	...
H	0.57	0.42	0.21	0.39	0.28	0.05	0.03	0.03	0.39	0.09	...	...
H_{1500}	0.55	...	0.27	...	...	0.05	0.06	0.03	...	...	...	...
H_{12000}	0.53	...	0.27	...	...	0.06	0.11	0.05	...	...	...	...
J	0.58	0.56	0.31	0.74	0.47	0.72	0.72	0.56	0.55	0.49	...	...
J_{1500}	0.54	...	0.31	...	...	0.65	0.62	0.57	...	...	...	...
J_{12000}	0.53	...	0.30	...	...	0.66	0.63	0.61	...	...	...	...

[1] Pendulum, ramp and ASTM C-1028 tests could not be made on the abraded samples due to the small available surface area.
[2] Test feet prepared with 400 grit paper.
[3] The subscripts to tiles G, H and J relate to the number of abrasive cycles.

Table 5 – *R_z surface roughness before and after abrasion.*

Abrasive cycles	R_z of Tile, µm					
	A	B	C	D	E	F
0	11.5	9.6	16.8	19.5	28.3	20.7
750	12.3	10.7	14.6	19.6	24.6	24.0
1500	13.2	12.3	15.6	19.9	25.6	25.1
12000	14.2	15.9	16.1	23.9	24.9	18.4

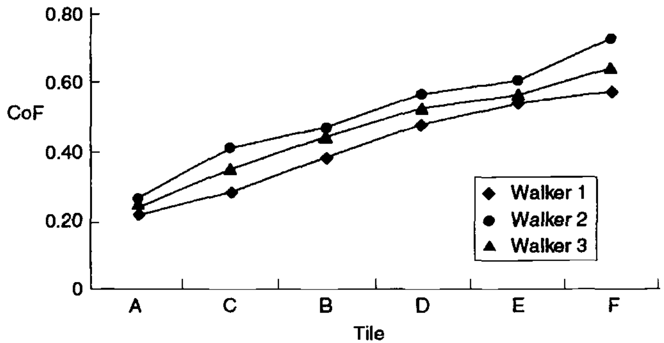

Figure 1 – *Influence of walkers on the RAPRA CH0001 test, where smooth Four S shoes are worn water runs over the specimens.*

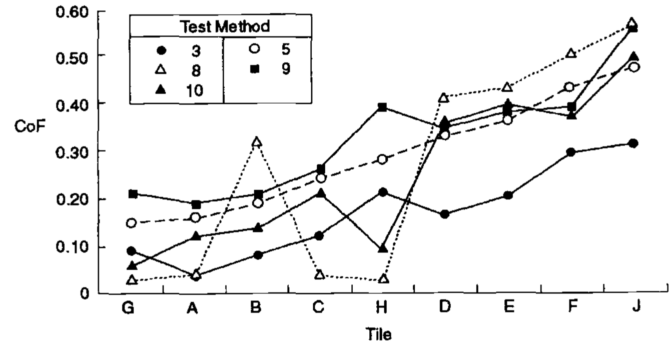

Figure 3 – *Comparison of TRRL rubber test results [SATRA (3); Pendulum (5; and VIT (8)] with wet barefoot (9) and oil-wet ramp(10) test results.*

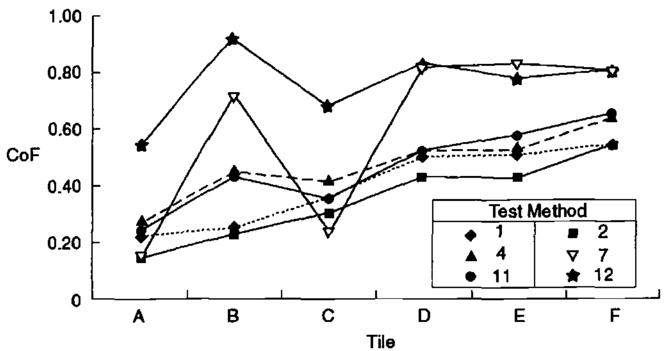

Figure 2 – *Summary of tests involving Four S rubber [SATRA, 400 N (1); SATRA, 100 N (2); Pendulum (4); shod-wet ramp (11)] and Neolite® Test Liner [VIT (7); and C-1028 drag sled (12)].*

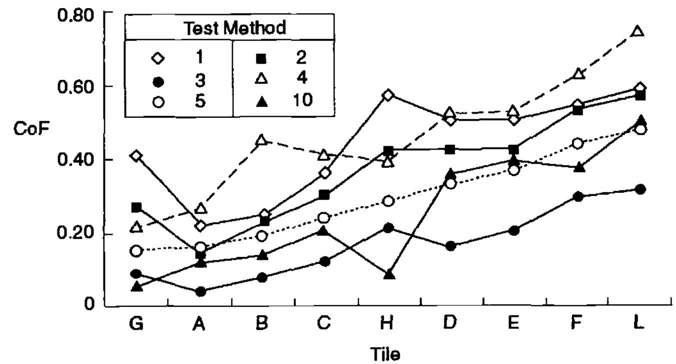

Figure 4 – *Comparison of SATRA [Four S, 400 N (1); Four S, 100 N (2); and TRRL (3)] and Pendulum tests [Four S (4) and TRRL (5)] with oil-wet ramp (10) tests.*

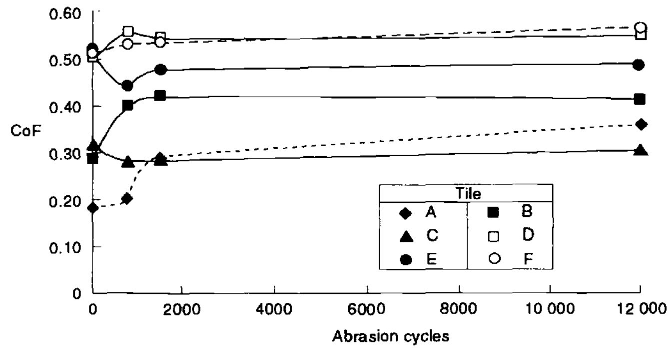

Figure 5 – *Effect of abrasion on SATRA results, Four S rubber.*

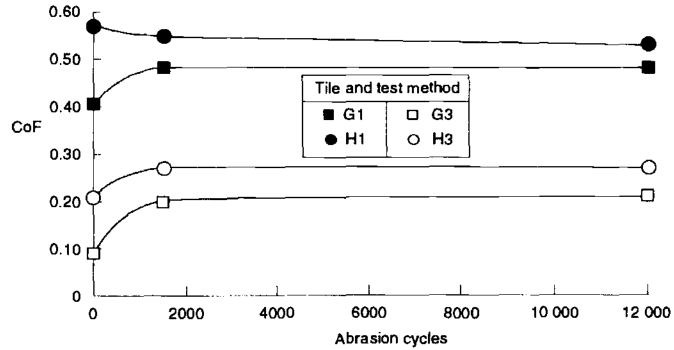

Figure 7 – *Effect of abrasion on SATRA slip resistance of new (G) and etched (H) porcelain tile, with Four S (1) and TRRL (3) rubbers.*

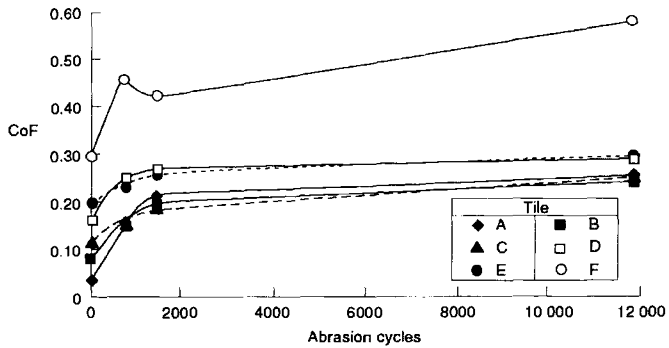

Figure 6 – *Effect of abrasion on SATRA results, TRRL rubber.*

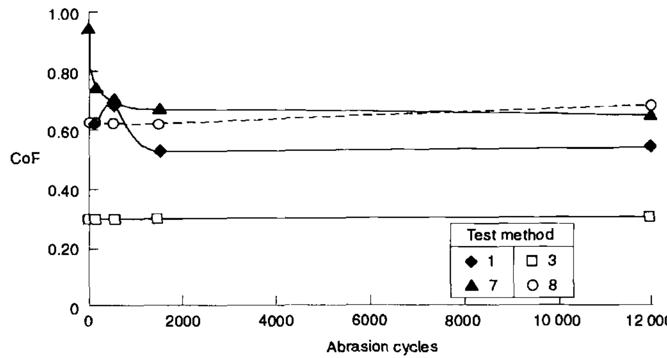

Figure 8 – *Effect of abrasion on SATRA [Four S (1) and TRRL (3)] and XL [Four S (7) and TRRL (8)] results for profiled tile K.*

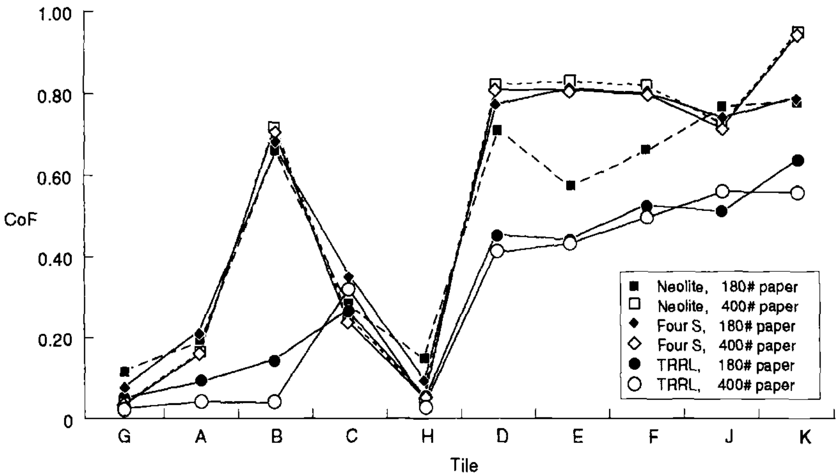

Figure 9 – *Summary of VIT results according to test foot and method of preparation.*

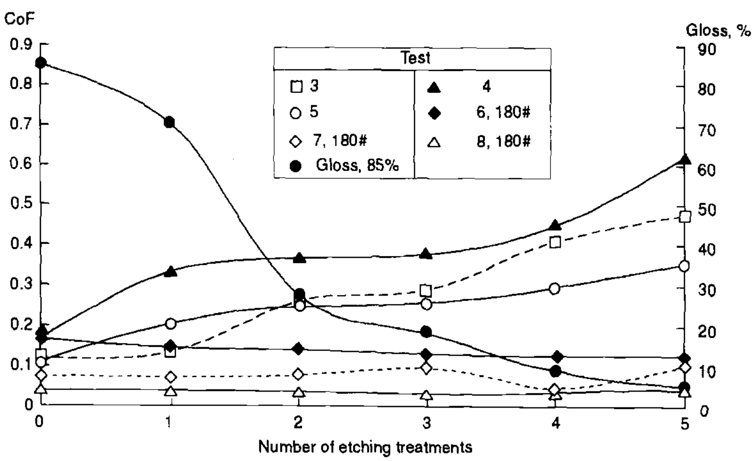

Figure 10 – *Effect of etching treatments on the slip resistance [SATRA, TRRL (3); Pendulum, Four S (4), TRRL (5); and VIT, Neolite® Test Liner (6), Four S (7) and TRRL (8)] and gloss of polished tile.*

The results have been plotted graphically to enable a direct comparison of the results, where it is possible to obtain a visual sense of how the ranking of the results differs, and where individual results or groups of results deviate from a trend established by the other results. The graphical representation also allows a comparison of differences in the relative magnitude of the results. The use of figures has been preferred to presenting the data as a series of correlations between the test methods due to the limited size of the data sets presented here. When larger sets of data are compared, the correlations can change. This may particularly be the case when resilient materials such as vinyls, rubbers and cork-based products are included in the comparisons.

The degree to which such results are reproducible needs to be considered. The VIT has been reported to have a 95% reproducibility limit of 0.09 and a 95% repeatability limit of 0.05 [16, 17]. Although the Pendulum has been extensively used, such limits may not have been adequately determined (and might even be a function of the surface being measured). The ASTM E-303 precision and bias statement indicates a repeatability standard deviation of 1.0 BPN units (roughly equivalent to 0.01 coefficient of friction).

The Pendulum results for tiles A to F are the outcome of an interlaboratory study, where CSIRO and 25 other laboratories assessed 780 tiles (six sets of five tiles each). The repeatability standard deviation for the six sets of tiles averaged 1.4 BPN units (for both the Four S and TRRL rubbers). The largest individual mean result was typically 30% above the group mean, and the smallest 15% below. Thus if a tile had a group mean of 40 BPN units, the individual laboratory mean results might range from 34 to 52 units. After six sets of outlying results were variously withdrawn for each tile type, most of the remaining results then fell within 10% of the group mean. When a coefficient of friction of 0.40 provided a pass and 0.39 a failure, it can be appreciated that too much faith has been placed on the absolute accuracy of the results.

Where the trend lines for two sets of data coincide, but are almost parallel, the correlation may be lower because of multicollinearity effects than where similar trend lines are widely separated. Where correlation of a tribometer with human experience is used to justify the use of a test method on specific types of surfaces, the establishment of appropriate compliance criteria needs to include a consideration of the difference in the magnitude of the results.

Discussion of Experimental Results

Several recent studies of the wet slip resistance performance of tribometers have concentrated on measurements of a limited number (two or three) of smooth surfaces (e.g. stainless steel, float glass, vinyl, glazed ceramic, marble and quarry tiles) using a single type of hard test foot (Neolite® Test Liner); for example [16–18, 22].

The results obtained in this study tend to point out some anomalous behaviour when different slip resistance test methods are used to rank a wider range of ceramic tile surface textures. However, this study itself forms part of a wider on-going study of the slip resistance of stone, concrete, vinyl, rubber, and other pedestrian surfaces. Care should be taken in extrapolating from these initial results, as one should expect there to be exceptions to the general trends observed with these ceramic tiles.

Ramp Test Results

Figure 1 indicates there was a consistent difference between three ramp walkers when wearing shoes shod with Four S on wet specimens. In order to facilitate interlaboratory comparisons, ramp tests should have calibration boards – standardized ramp surfaces – whereby results can be corrected to allow for differences between walkers. It has been shown that this enables a significant reduction in the variation of the results [9].

The wet shod ramp (RAPRA CH0001) test results were very similar to the wet Four S Pendulum test results (Figure 2). This is not surprising since the RAPRA test uses footwear shod with smooth Four S rubber. This tends to validate the use of the Pendulum where the soling materials and contamination conditions are very similar. However, even though the results were so close as to be almost interchangeable (within the presumed limits of reproducibility for each test), the correlation coefficient was 0.88.

The wet barefoot ramp test is the only practical test method for determining wet barefoot slip resistance. The ramp test results are considered [11] to provide a reliable indication of slip resistance under the type of condition being tested (wet barefoot, oil-wet with profiles sole texture, water-wet with smooth soles).[11] Where a tribometer is being used to test a similar set of conditions, the ramp tests provide a sound basis for comparison. However, where the test results are dissimilar, it may still be possible to develop correlations for walking on horizontal surfaces. For example, the wet barefoot ramp and the wet TRRL Pendulum tests had a correlation coefficient of 0.94.

The wet barefoot ramp coefficients of friction are slightly greater than the wet TRRL Pendulum test results, with the largest difference being measured on the etched porcelain tile (Tile H, Figure 3). The harder Four S rubber gave significantly higher results than the wet barefoot ramp test (correlation coefficient of 0.92). Given the soft yielding nature of the sole of the human foot after prolonged water immersion, resilient test feet are likely to provide a better surrogate for the assessment of wet barefoot slip resistance.

The oil wet ramp coefficient of friction results were slightly less than the wet TRRL Pendulum test results (0.95 correlation coefficient). The Four S Pendulum correlation was 0.87, which may reflect that the nitrile rubber sole of the treaded boots has a IRHD hardness of 72. The largest difference between the oil wet ramp and the pendulum results was again measured on the etched porcelain tile This reflects the difference in viscosity between oil and water, and also the smooth macrotexture of this tile.

Choice of Test Foot Material

The hard Neolite® Test Liner and Four S test feet, when prepared with 400 grit paper, gave almost identical VIT results. For the three test methods where the TRRL and Four S test feet were compared (SATRA STM 603, Pendulum, VIT), the resilient TRRL rubber gave lower results than the harder, but less abrasion resistant Four S rubber.

One might expect that the TRRL rubber would lose more energy due to gross and reversible micro deformation than the Four S rubber, but would lose less energy due to abrasive wear. The selection of test foot material obviously has an influence on the magnitude of the coefficient of friction, but when the tiles are ranked in order of slip resistance for a given test method, the position of the products changes only slightly. However, such deviations may provide indications of the interacting energy dissipation mechanisms that occur when specific products are being tested. The ensuing insights should help to establish a basis for determining whether a certain test protocol is appropriate for assessing the slip resistance of a particular product in specific anticipated environmental exposure conditions.

The roughness of the test feet influences the measured coefficients of friction. The inherent roughness of some walkway surfaces will modify the roughness of test feet during the course of testing. The transient nature of the initial results that are obtained, as the

[11] The development of the HSL SOP-12 test at the British Health and Safety Executive supports this contention.

test foot is being conditioned by the walkway surface, needs to be recognised. Inclusion of such results may bias the mean test results. In such circumstances, it may be appropriate to conduct further tests where the test procedure is modified by adopting an appropriate method of preparing the test foot.

ASTM C-1028 Test Results

This test gives far higher results than the other tests, particularly on the smoother surfaced tiles (Figure 2). These results support the argument that wet slip resistance measurements should not be made using test methods where the test foot substantially resides on the surface prior to final test force application (thereby permitting the water to be squeezed out). Regardless of this, the ASTM C-1028 compliance requirement of 0.5 appears too generous to be a reliable indicator of safe or acceptable wet slip resistance. Furthermore, manually operated horizontal pull testers are considered unreliable due to uncontrolled, non-uniform and non-repeatable application of force and rate of force application. The ASTM C-1028 results had a 0.9 correlation coefficient with the XL VIT for both the hard Neolite® Test Liner and Four S rubber test feet.

SATRA STM 603 Test Results

With Four S rubber and a 400 N vertical load, there was good correlation between the STM 603 and the RAPRA ramp test results, except for tile B, and to a lesser extent, tile F, the other severely profiled tile. Reducing the vertical load to 100 N resulted in slightly lower results than at 400 N, except in the case of the coarse textured tiles (B, F and J) where the results were similar. The difference in results was larger with the very flat polished porcelain tiles (G and H), where slip-stick behaviour was observed at 400 N. A 100 N load would be more appropriate for these tiles, as the 400 N results \overestimate the slip resistance compared to the other test methods (Figure 4).

With the more resilient TRRL rubber, the STM 603 consistently gave lower results than the Pendulum. In the Pendulum test, the rubber test foot is mounted on a test foot that is spring loaded. This has the effect of causing the test foot to make intermittent oscillatory contact with the test surface over the 126 mm path length. This cyclic loading would cause increased energy losses due to gross and reversible micro deformation.

The STM 603 with TRRL rubber had good correlation with the Pendulum TRRL (0.93), the RAPRA Four S ramp (0.94), the oil-wet ramp (0.93) and the wet barefoot ramp (0.92) as well as the STM with Four S rubber (0.93).

With Four S rubber and a 400 N vertical load, the STM 603 gave much lower results than the Pendulum in the case of the coarse textured tiles (B, F and J), much greater results in the case of the very flat polished porcelain tiles (G and H), and slightly lower results in the case of the other tiles. The correlation coefficient was 0.64. This difference in behaviour may relate to the degree of contact that is achievable between the test foot and the test surface, depending on the width of the test foot, the profile of the surface, the magnitude of the load, and whether the loading is continuous (STM 603) or cyclic (Pendulum).

The 0.2 s static delay time that was used for STM 603 measurements (when the load was applied to the test surface prior to commencing horizontal movement) does not appear to have any deleterious effect upon the measurement of wet slip resistance. Given that water can be squeezed out between surfaces where there is even a small residence time, this finding might appear surprising. However, unlike the ASTM C-1028 test where the full area of the 76 x 76 mm test foot is in contact with the tile surface, only the 25 mm wide trailing edge of the angled test test foot is in contact, simulating a condition where a slipping foot is still at an angle to the walkway surface.

English XL VIT Test Results

When compared to the other test methods, the VIT tends to underestimate the wet slip resistance of smooth polished, glazed or surface protected tiles, while overestimating the slip resistance of tiles with a textured or profiled surface. Use of the resilient TRRL rubber in the VIT gave better correlation than the hard Neolite® Test Liner and Four S rubber for tiles with a textured or profiled surface.

When the coarser 180 grit paper was used, the Neolite® Test Liner results were less extreme, in that there was a slight increase in the slip resistance of the smooth surfaces, and a decrease in the slip resistance of the tiles with a textured or profiled surface. The largest decreases were observed with tiles D, E, F and K. These results are inconsistent with the general finding [22] that the coefficient of friction rises with increasing roughness of the soling material.

Unlike the other water-wet test methods, the VIT did not detect an improvement in slip resistance due to acid etching. This is contrary to the findings of Di Pilla [23], who used a VIT to study the comparative effectiveness of ten floor surface treatment products on a glazed ceramic tile and a marble tile. Although the slip resistance of Di Pilla's untreated ceramic tiles varied significantly (from approximately 0.1 to 0.3), he detected a significant increase in slip resistance (to 0.4 and above) with six of the proprietary treatments. Given the limited reproducibility of the VIT [16, 17], the authors thought that the degree of etching might have to exceed a threshold before the VIT could detect a significant improvement. However, even when several etching treatments eliminated the gloss on the polished porcelain tile used in this study, the VIT was unable to detect an increase in slip resistance, see Figure 10. Porcelain tiles are typically more chemically resistant than ceramic tile glazes, and are much more chemically resistant than marble.

The VIT's overestimation of the slip resistance of tile B, when compared with the ramp and SATRA STM 603 tests, is of greater concern. This tile has a high gloss glaze coat and contains coarse grit particles that protrude above the background. The high VIT results suggest that the test foot interacts with the grit, but the vertical pressure is insufficient, particularly at low angles, for the test foot to interact with the high gloss glaze. The lower ramp test results and real world experience (the tiles were withdrawn from the market) suggest that the high gloss glaze determines the initially available pedestrian traction, rather than the coarse protruding grit particles.

The VIT results for the Neolite® Test Liner and Four S rubber test feet are very similar when they are prepared with 400 grit paper. When these rubbers were used in the VIT, they overestimated the slip resistance of tile D with respect to tile J, contrary to all the other test methods. However, when the 180 grit paper was used, this anomaly was corrected with the Neolite® Test Liner, but not the Four S rubber. These results confirm earlier findings [24] that the VIT results can depend on how the test foot is prepared. No specific control was exercised on the applied vertical force when preparing test feet in this study. The UK Slip Resistance Group [25] recommends the use of 400 mesh sandpaper when preparing test feet for Pendulum testing. However, on smooth floors, a fine 3 μm lapping film is also used to prepare test feet, to ensure that the coarser surface roughness of the test foot does not inhibit the generation of a water film between the test foot and the floor.

Pendulum Test Results

The small difference between the RAPRA ramp tests and the Four S rubber Pendulum tests suggests that the Pendulum provides an excellent approximation of pedestrian slip resistance under these specific conditions (smooth Four S rubber footwear and water), even though the correlation coefficient was 0.88. While the Four S rubber results are much greater than those obtained with TRRL rubber (0.93 correlation coefficient), the only significant difference in ranking performance occurs with tile B (Figure 4). The Four S rubber Pendulum results tend to overestimate the slip resistance of tile B with respect to the wet barefoot and oil-wet ramp tests. This is possibly due to the poor abrasion resistance of the Four S rubber, given that coarse grit protrudes above a high gloss glaze in this tile. Loss of energy associated with abrasion of the rubber may be inducing an increased pendulum result that does not relate to the available friction. On roads, where TRRL rubber has been traditionally used, one assessment was that about 80% of the Pendulum reading is due to the road surface microtexture and 20% due to its macrotexture [26].

If one accepts that the TRRL rubber makes little contribution to friction on wet smooth surfaces, one might also assume that the TRRL Pendulum results correctly rank the slip resistance of the tiles. The STM 603 and the pendulum had better correlation when TRRL rubber was used (0.93 as compared to 0.64 for Four S rubber at 400 N). However, when assessing the degree of correlation between STM 603 and Pendulum test results, one should look at the effect of loads and consider the specific type of walkway surface material being studied.

The TRRL Pendulum results closely follow those of the wet barefoot ramp tests, tending to be about 0.025 lower, except in the case of the unglazed terracotta and polished porcelain tiles. It is most important to recognise that the wet barefoot ramp test is providing an indication of the available slip resistance of the surface when installed as a horizontal walkway. As a pedestrian walks with a longer stride or at a faster pace, the required slip resistance will increase. The required slip resistance will similarly increase if the surface material is installed on a sloping walkway. The wet barefoot ramp test results do not indicate the angle at which it is safe to install the surface.

The German requirements for barefoot slip resistance in public areas can be considered to commence at an angle of 18 degrees, equivalent to a coefficient of friction of 0.325. Since the wet barefoot ramp test can only be conducted in a laboratory, a wet pendulum test with TRRL rubber could be used as a *de facto* ramp test method on some surfaces, where a value of 0.35 or greater might indicate satisfactory wet barefoot slip resistance (based on a wider study of more than 80 pedestrian surfaces). However, the appropriateness of such an extrapolation should be confirmed by suitable laboratory investigations in each case until the practice is accepted for specific product ranges.

Effect of Acid Etching

The SATRA STM 603, Pendulum and wet barefoot ramp tests were all able to determine an improvement in the slip resistance of the etched polished porcelain tile. The VIT and oil-wet ramp tests were unable to detect an improvement. Since oil is far more viscous than water, it was not expected that the oil-wet ramp would be able to detect the effect of acid etching.

Effect of Glaze or Surface Stain Protection

Tile D was similar to tile J, other than tile D had a protective surface coating (similar to a glaze but much thinner). The presence of the surface coating on this profiled surface resulted in a lower coefficient of friction with all test methods except the VIT when the hard Four S and Neolite® Test Liner rubbers were prepared with 400 grit paper.

Tiles A and G had the same porcelain body. Tile A was surface protected, while tile G had a limited amount of internal porosity exposed by the surface polishing treatment that the tile had been subjected to. The SATRA STM 603 and Pendulum tests yielded contradictory results for both rubbers (Figure 4).

Effect of Abrasion

The effects of abrasion have to be considered in terms of how the microtexture of each tile changes, as well as how the surface energy states may change, as measured by contact angles. Although the contact angle measurements that were made on some of the tiles confirm a change in the surface energy, this aspect is not considered further in this paper. One thousand five hundred abrasion cycles was generally sufficient to induce enough wear, whereafter there was generally little change in the slip resistance. However, in practice, one needs to look at the specimens to determine the extent to which the glaze or surface protection has been removed, or the body of an unglazed tile has been exposed. One also needs to consider how homogeneous or heterogeneous the surface of the product is, and the uniformity of the wear. Multiple use of the abraded tiles for making several slip resistance measurements has an associated risk of not always having a pristine surface available for testing.

With Four S rubber in the SATRA STM 603, abrasion resulted in improved slip resistance in tiles A and B that had high gloss (smooth) surface (stain) protection and glaze respectively (Figure 5). These changes were accompanied by a slight but consistent increase in R_Z surface roughness. The initial loss of slip resistance in tile C, and a subsequent slight recovery, was reflected in an initial loss of surface roughness, followed by a slight recovery. The initial improvement in the slip resistance of tile D was reflected in an increase in surface roughness. In tile E, the initial loss of slip resistance was also associated with a loss of surface roughness. In tile F, there was a very slight increase in slip resistance, which correlated with an initial increase in surface roughness. There was ultimately an overall loss of surface roughness, but with a further slight increase in the slip resistance. This was possibly due to increased porosity at the tile surface, as the "skin" of this extruded unglazed tile was removed.

With TRRL rubber, there was a general increase in slip resistance with abrasion up to 1500 revolutions (Figure 6). The slip resistance of unglazed tile F was significantly higher after 12000 abrasion cycles.

The slip resistance of the polished porcelain tile (G) increased with abrasion with both rubbers (Figure 7). A proprietary etching treatment increased the STM 603 slip resistance, as measured with both rubbers. Abrasion of the etched tiles caused a decrease in the slip resistance with the Four S rubber, but a further increase with the TRRL rubber. Although similar measurements were made with the VIT, using Neolite® Test Liner, Four S and TRRL rubbers, there were no pronounced changes in the observed slip resistance. In the case of tile J, the porcelain tile with a spatterdash finish (results not plotted) there was a decrease in slip resistance with abrasion for the Four S rubber, for both the STM 603 and the VIT. With the TRRL rubber, a very slight increase in slip resistance with abrasion was observed with the VIT, but no change was detected with the STM 603.

In the case of tile K, the porcelain tile with a pronounced series of ridges, no change in slip resistance was detected with the TRRL rubber with either the STM 603 or the VIT (Figure 8). However, the VIT recorded a decrease in slip resistance with abrasion with the Four S rubber. The STM 603 recorded an overall decrease in slip resistance, having detected an increase after 750 revolutions.

The abrasive treatment that was used in this study uses white fused alumina of F 80 grain size. It might be thought that this would lead to abraded surfaces that are quite similar in terms of surface roughness, but this was not observed. However, the initial topography and textures of the tiles were quite dissimilar, and the macrotexture of the tiles was relatively unchanged by the abrasion process.

Surface Roughness Measurements

R_z surface roughness measurements can provide a useful indication of the extent to which a homogeneous surface is being modified on a microtextural level where the wear process is uniform. However, there is a great difficulty in comparing roughness results obtained on smooth surfaces, with those surfaces that have a coarse heterogeneous texture or profiling. The Surtronic 10 used to make the roughness measurements has a stylus with a 5 μm radius tip that traverses a 4 mm length of the test surface, divided into five cut-off lengths of 0.8 mm. Since the raised spatterdash surface features on tiles D and J are up to 5 mm in diameter, the use of a device that permits longer cut-off lengths should be beneficial. The reproducibility limit of the Surtronic 10 device used has not been determined, but would logically depending on the surface topography. While the use of additional surface texture parameters may provide a better indication of the surface topography [27], one ideally needs to define both the microtextural and the macrotextural characteristics and to consider their relative influences.

Concluding Remarks

The tiles studied represent a reasonable range of surface textures and traction characteristics. The topography and surface texture definitely influence the results, as does the nature of the rubber test foot used. This study has considered the proposition that the relative slip resistance of materials can be determined by ranking them against standardised materials. Some surfaces may cause some tribometers to overestimate the available traction, leading to potentially dangerous situations. It is recommended that if such a ranking system is introduced, tribometers should undergo a rigorous qualification process with respect to the types of surfaces that they are fit for testing.

The manually operated horizontal pull tester (C-1028) was unable to satisfactorily distinguish between the wet slip resistance of the tiles. Since this test method significantly overestimated the wet slip resistance of tiles that offer little available traction, it should be withdrawn, in line with previous theoretical recommendations [1,2,28].

The process of making a slip measurement may modify the surface of the test foot and the tile surface [29]. In the case of the Four S rubber, which has poor abrasion resistance, coarse surfaces roughen the test foot, while smooth surfaces tend to polish it. This process is less pronounced in the highly resilient TRRL rubber, but in both cases, a thin film of rubber may be deposited on the tile, thus modifying the tile surface. It is well-known that when a Four S test foot is used in the Pendulum tester, the indicated slip resistance of a smooth product will continue to decrease as the test foot is slowly polished. This has led to the sensible UK Slip Resistance Group recommendation [25] that the Four S test foot be prepared on a 3 μm pink lapping film, whenever a product has a surface roughness less than 15 μm R_z. The English XL VIT results are also considered sensitive to the method of test foot preparation in terms of the sanding protocol [24].

These experimental results raise important issues with respect to the meaning of slip-resistance measurements. One such issue, for example, is the relative accuracy of walkway-safety tribometer tests. If the available slip resistance of a new product is overestimated, it may be used in situations where there is an insufficient factor of safety. Dangerous situations will persist if slip audits overestimate the available traction. If the available slip resistance of a new product is underestimated, it may not be used in situations where it is eminently suitable for use. If a tribometer underestimates the available traction of an existing walkway surface, unnecessary remedial work might be undertaken.

Tiles A to F were used in an interlaboratory Pendulum study where 750 tiles were assessed by 25 other laboratories. While it was presumed that each set of tiles was identical, the tiles were not individually tested before being sent to all the laboratories. Although differences in the slip resistance of individual tiles might account for some of the large variation that was observed, one must ask the questions "How much reliance should be placed on individual results?" and "How do these results relate to real world traction demands?" The least variation was typically seen in laboratories with Registered Testing Authority status for the Pendulum test. This confirms the value of laboratory accreditation schemes and the need for certification of operators[12]. Controlling variations within a production batch is also of concern, as is accurately representing the predictable minimum slip resistance [30].

The extent to which the slip resistance of a product is sustainable over its anticipated life cycle is another important issue. If the available friction decreases significantly, some

[12] Richard Bowman, the principal author of this paper, is a Certified XL Tribometrist, and a NATA (National Association of Testing Authorities, Australia) assessor of laboratories accredited to conduct the Pendulum test.

products will not be fit for an intended purpose. Architects can only specify products based on the information that is provided to them, and manufacturers currently provide no indication of how the slip resistance is likely to vary with time or specific types of exposure conditions.

The SATRA STM 603 tester can detect noticeable variation between and even within the face of the quarry tiles that are used for its calibration. Analysis of a wider set of data (on other walkway surfaces) indicates that when TRRL rubber is used in both the SATRA STM 603 and Pendulum, there is better correlation between results than when Four S rubber is used. There is also better correlation between SATRA STM 603 and ramp results when TRRL rubber is used. The variation in coefficient of friction that occurs with the load applied in the SATRA STM 603 tester appears to be a function of the texture of the surface tested. Larger (400 N) loads may cause the available friction to be overestimated when Four S rubber is used on some surfaces. However, 400 N is the load specified in SATRA TM 144, and the minimum load in prEN 13287:2002, Safety, Occupational and Protective Footwear for Professional Use – Test Method for the Determination of Slip Resistance. While a 400 N vertical load is approximately half body weight, some researchers [4, 5] have reported a vertical load of about 200 N at heel strike, and that the vertical force often decreases rapidly after a slip has been initiated. Adjustment of the SATRA STM 603 test load and speed parameters may provide greater biofidelity for specific situations. In order to determine the relevance of SATRA STM 603 results, they should be compared with ramp test results (or those obtained by subjects on force plates). The same principle applies to results obtained with the Pendulum and the VIT. The VIT, depending upon the specific test conditions, appears to be prone to both overestimation and underestimation of the available wet slip resistance. Further study should be directed at establishing whether it simulates initial foot contact during gait with respect to measuring slip resistance [31].

Chang and Matz [32] found that the ranking of footwear materials based on their slip resistance values depends highly on the slipmeters, floor surfaces and surface conditions. They concluded that such differences were statistically significant, and that it is necessary to use multiple samples for material testing. The current study also found that the use of multiple walkway surface samples provides a better indication of the relative performance of individual tribometers. It is recommended that a broad range of walkway surfaces be used when determining the ability of tribometers to determine available pedestrian friction. It is also recommended that a wide range of walkway surfaces should be used in biomechanical studies when determining utilized pedestrian friction.

While not widely used by slip resistance experts within the USA, the Pendulum when used with TRRL rubber (as in ASTM E-303) provided reasonable results. When selecting test feet for use in tribometers, their characteristics and influence on performance need to be better appreciated. The use of combinations of devices and test feet should be restricted based on comparable performance with tests involving human subjects. Where ramp tests are used, calibration surfaces are required to correct results, as this significantly improves the accuracy of the test and provides a means for interlaboratory standardisation. If a ranking system is to be introduced, the inherent limitations of tribometers need to be recognised, and their use restricted to situations where the results have been demonstrated to be reliable.

To sum up, architects want certainty when specifying, and prefer simple systems. Risk management considerations require a prediction of future available traction. The European Construction Products Directive adopts a sensible approach in that products must be safe (slip resistant) at the end of their service life. Manufacturers should ideally test products both when new and after an appropriate accelerated wear test, before reporting the lower figure and the specific test specimen preparation protocol.

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