WORK SURFACE FRICTION: DEFINITIONS, LABORATORY AND FIELD MEASUREMENTS, AND A COMPREHENSIVE BIBLIOGRAPHY

by

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This report is actually three separate reports under one cover. The first report is "Slippery" vs. "Slip Resistant" Work Surfaces: The Background for a Regulatory Definition by James M. Miller. The second [redacted] by Don B. Chaffin and Robert O. Andres. The final report is A Bibliography of Coefficient of Friction Literature Relating to Slip Type Accidents by James M. Miller. The work was sponsored by OSHA, and took place primarily in the summer of 1982.

0272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO. IOE/CE - 83/02

2.

3. Recipient's Accession No.

. Title and Subtitle

"Slippery" vs. "Slip Resistant" Work Surfaces:
The Background For a Regulatory Definition

5. Report Date

February 1983

6.

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8. Performing Organization Rept. No.

. Performing Organization Name and Address

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10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C) B9F26034

(G)

2. Sponsoring Organization Name and Address

ccupational Safety and Health Administration
.S. Department of Labor
00 Constitution Avenue
ashington, D.C. 20210

13. Type of Report & Period Covered

FINAL REPORT

14.

5. Supplementary Notes

. Abstract (Limit: 200 words)

There has been over fifty years of scattered research into the areas of alking/working surface slipperiness and coefficient of friction (COF) easurement. In spite of this research, numerous standards address slip/ all type accidents only in terms of requiring surfaces to be qualitatively non slippery". This paper summarizes that literature useful in providing uidelines for establishing quantitative criteria for "slippery" vs. "slip esistant" combinations of surface, shoe, task, and contaminant conditions.

Recommendations applicable to standards making organizations are made. mong them are: (a) changing legally inappropriate descriptor terms such s "non-slip" to "slip resistant"; (b) defining "slippery" vs. "slip esistant" in terms of quantitative COF values (i.e., for persons walking nloaded on level surfaces a COF of 0.5 would be a reasonable standard); c) modifying standards to emphasize that "slip resistance" requirements ay be met more easily by controlling the type shoe, type task, or amount f surface contaminant rather than controlling only the COF of the basic urface and its coating.

Additionally, these questions key to the area and still unanswered are umarized, providing directions into which future research efforts might e directed.

. Document Analysis a. Descriptors

riction, Slips, Falls, Slippery, Slip Resistant, Floors, Shoes,
ork Surfaces, Measurement of Friction, Coefficient of Friction

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

Availability Statement:

Unlimited

19. Security Class (This Report)

20. Security Class (This Page)

21. No. of Pages

22. Price

50272-101

REPORT DOCUMENTATION PAGE	**1. REPORT NO.**	**2.**	**3. Recipient's Accession No.**

4. Title and Subtitle

Evaluation of Three Surface Friction Measurement Devices for Field Use

5. Report Date

September 1982

6.

7. Author(s)

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8. Performing Organization Rept. No.

9. Performing Organization Name and Address

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10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.

(C) B9F16955 and
B9F26440
(G)

12. Sponsoring Organization Name and Address

Occupational Safety and Health Administration
U.S. Dept. of Labor
200 Constitution Avenue
Washington, DC 20210

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Several measurement devices and techniques have been developed through the past 50 years in an attempt to quantify the static coefficient of friction (COF) of shoe and floor surface interactions. Much of this work has been laboratory research with bulky equipment, but recently portable measurement devices have evolved to the extent that field measurements can be taken. Three such devices (Bigfoot, Slipometer, and NBS-Brungraber) were tested in laboratory and field studies for their consitency, repeatability, ease of use, and accuracy. All three devices successfully quantized the static COF of a variety of shoe and floor materials, but all three devices had specific problems in both the laboratory and the field settings. With slight modifications, the devices could all have been improved for field applications. However, the experience gained through this study leads to the recommendation that the dynamic COF needs to be considered, also.

7. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

. Availability Statement

Unlimited

19. Security Class (This Report)

20. Security Class (This Page)

21. No. of Pages

22. Price

EVALUATION OF THREE SURFACE FRICTION MEASUREMENT DEVICES FOR FIELD USE

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September, 1982

ACKNOWLEDGMENTS

We would like to express our gratitude to the several agencies, companies, and individuals who made this study possible. The Consumer Product Safety Commission supplied the NBS-Brungraber device, Creativity, Incorporated loaned us the Slipometer, and Safety Sciences, Incorporated sent us instructions so we could construct our own Bigfoot. Five different companies cooperated by permitting us to make measurements in their facilities; the field studies would not have occurred otherwise. Thanks to Jacques Phillips, President of Safe-Walk, Incorporated, and Dr. Robert Brungraber for providing us with invaluable advice about past studies and techniques. We would also like to thank Mark Redfern and Charles Woolley for technical assistance, and Ellen Amaya for typing and editing this report. This study was supported by two OSHA personal service contracts: B9F16955 and B9F26440.

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I. Introduction

The incidence and severity of trauma resulting from a worker's foot slipping is acknowledged by occupational safety authorities as a major concern. It is clear that foot slippage can lead to various types of falls, both when walking on a level surface or when leaning-over or climbing on elevated surfaces. In addition, foot slippage can cause over-exertion injuries due to the unexpected muscular action necessary to attempt to recover from a slip. Because of this, the resulting reports of injury may not indicate foot slippage as the primary cause of the injury. Despite this, it is estimated that over 20% of worker's compensation costs each year are a result of fall or slip related injuries (Szymusiak and Ryan, 1982).

At present the Occupational Safety and Health Administration and the American National Standards Institute are concerned that work surfaces of all types may not be sufficiently designed to stop unnecessary foot slippage, and yet provide other qualities desired by their users (i.e., wearability, sanitation, appearance, low cost, etc.). To determine whether work surfaces are especially slippery under a variety of work conditions it was deemed necessary to be able to measure the frictional qualities of different work surfaces in the work setting. This general objective has also been espoused in the past by the National Bureau of Standards with particular concern for flooring in public buildings (Brungraber, 1976) and by The International Technical Centre for Rubbers and Plastics in Great Britain (James, 1980). Because of this past interest, several different empirical approaches have been developed to determine surface friction quality. Some of these have resulted in devices suitable for field use, three of which were selected for more intense evaluation in this study.

1.1 Objectives and Evaluation Criteria

The objective of this study can be stated as follows:

To evaluate three surface friction measurement devices to determine their capability to estimate the frictional quality of floor surfaces in the workplace.

It was deemed necessary at the outset of the project to evaluate the performance capability of the devices with respect to the following criteria:

1. Consistency between devices. This criterion is used to identify if a device is consistently reading differently than its counterparts, and what conditions may affect such a bias if one exists.

2. Repeatability. This criterion requires the comparison of multiple readings from each device to determine its variability when used in different experimental conditions.

3. Ease of use. Subjective ratings, comments of two experienced operators, and the time required to setup and use the devices in various settings are used to determine a device's ease of use.

4. Accuracy. The accuracy of a measuring device reflects its ability to measure a basic phenomenon, which in this case is the surface coefficient of friction as determined by measurement of shear and normal forces induced by the measuring devices when acting on flooring materials mounted on a Kistler Force Platform.

1.2 Technical Background on Surface Friction Measurement

The force developed between two contacting surfaces which acts parallel to the contacting surfaces and resists any sliding of the materials is referred to as the Force of Friction. When a person walks the foot striking the floor surface creates both a normal and shear force component, as depicted in Figure 1. If the shear forces are larger than the force of friction then the foot slips until muscular reaction or an external force (i.e., hitting against object) alters the shear forces.

Early French physicist M. Amontons (1699) is credited with the following relevant concepts:

$$\text{Force of Friction} = \mu \cdot \text{Normal Force}$$

where μ is referred to as the coefficient of friction or COF, and is simply a ratio of the normal force holding two materials together and the maximum force necessary in shear to resist sliding. He further argued that the contact area would not affect values of COF; an argument that appears to apply to the present application (Brungraber, 1976). Furthermore, C. A. Coulomb (1781)

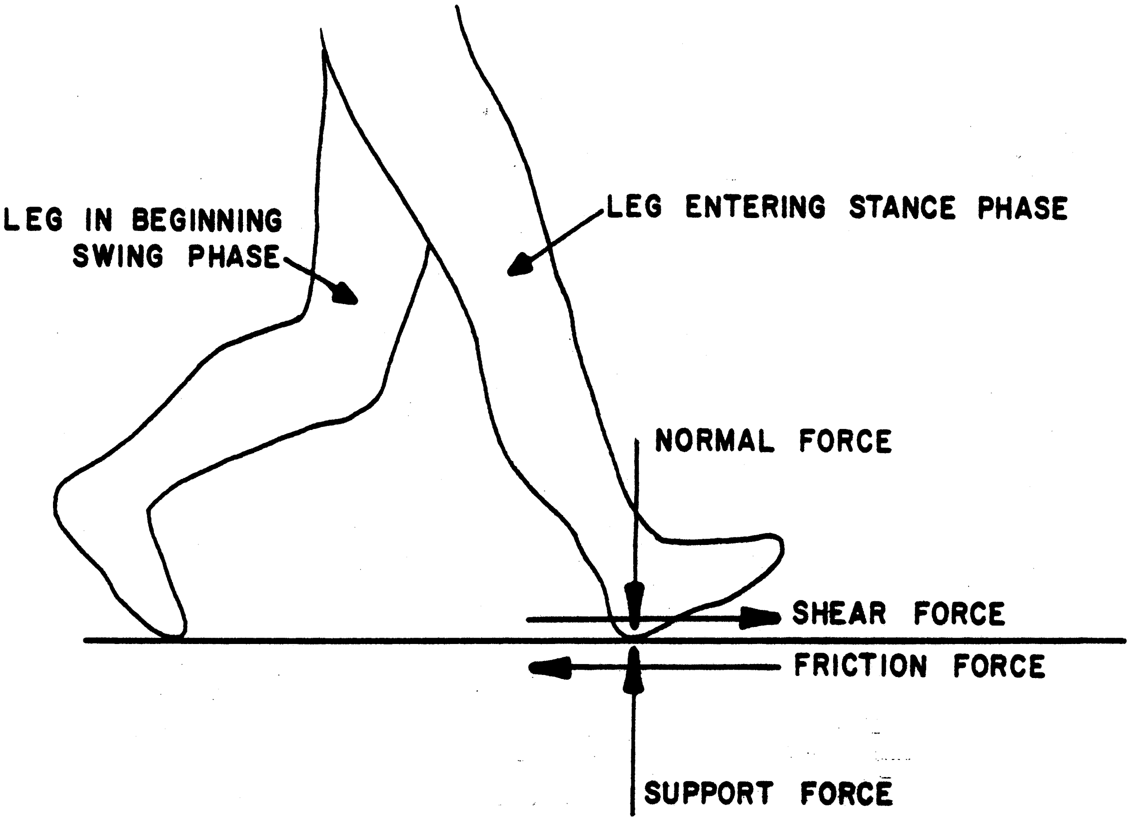


FIGURE 1. FORCES OPERATING AT FOOT WHEN HEEL STRIKE OCCURS DURING STANCE PHASE OF WALKING. SIMILAR FORCES EXIST AT TOE BEFORE IT LIFTS-OFF TO BEGIN SWING PHASE.

showed that the COF decreases with velocity of sliding once movement occurs, and hence static friction will normally be larger than dynamic friction measured during motion. More recent thinking on this latter concept by James (1980) questions this since some shoe and floor materials exhibit friction forces that increase at low velocities. This matter is also discussed by Brungraber (1976) and is illustrated in Figure 2. Because of the complexity in the way friction behaves, especially with new shoe and floor materials and the presence of contaminants and lubricants, simple measurement devices will always approximate the friction process. What is ultimately needed is a measurement device which simulates a person walking at various speeds with different stride characteristics and anthropometry. Such a device has been recently built by Perkins and Wilson (1982) for laboratory studies. Unfortunately such a machine is possibly very difficult to use in the field. At this time much simpler devices are proposed, mainly oriented towards the measurement of friction with a relatively slow onset of force application. The proponents of these simple devices argue that in normal walking the foot contacts the floor in a way that can be treated as a static problem provided frictional forces are large at low velocities. In other words, dynamic effects are irrelevant if a high friction force exists with static or low velocity conditions. Other experts argue that under some conditions, (e.g., dry rubber on vinyl tile) the frictional forces could increase with velocity (James, 1980). The argument continues that by providing such a quality in shoes and flooring it would be possible for a person to better control a slip once begun. Unfortunately, to be able to guarantee the combinations of conditions necessary for such an effect would be difficult in many work situations. One must concede, however, that this effect is real, and hence static friction measurements may over-estimate the slip

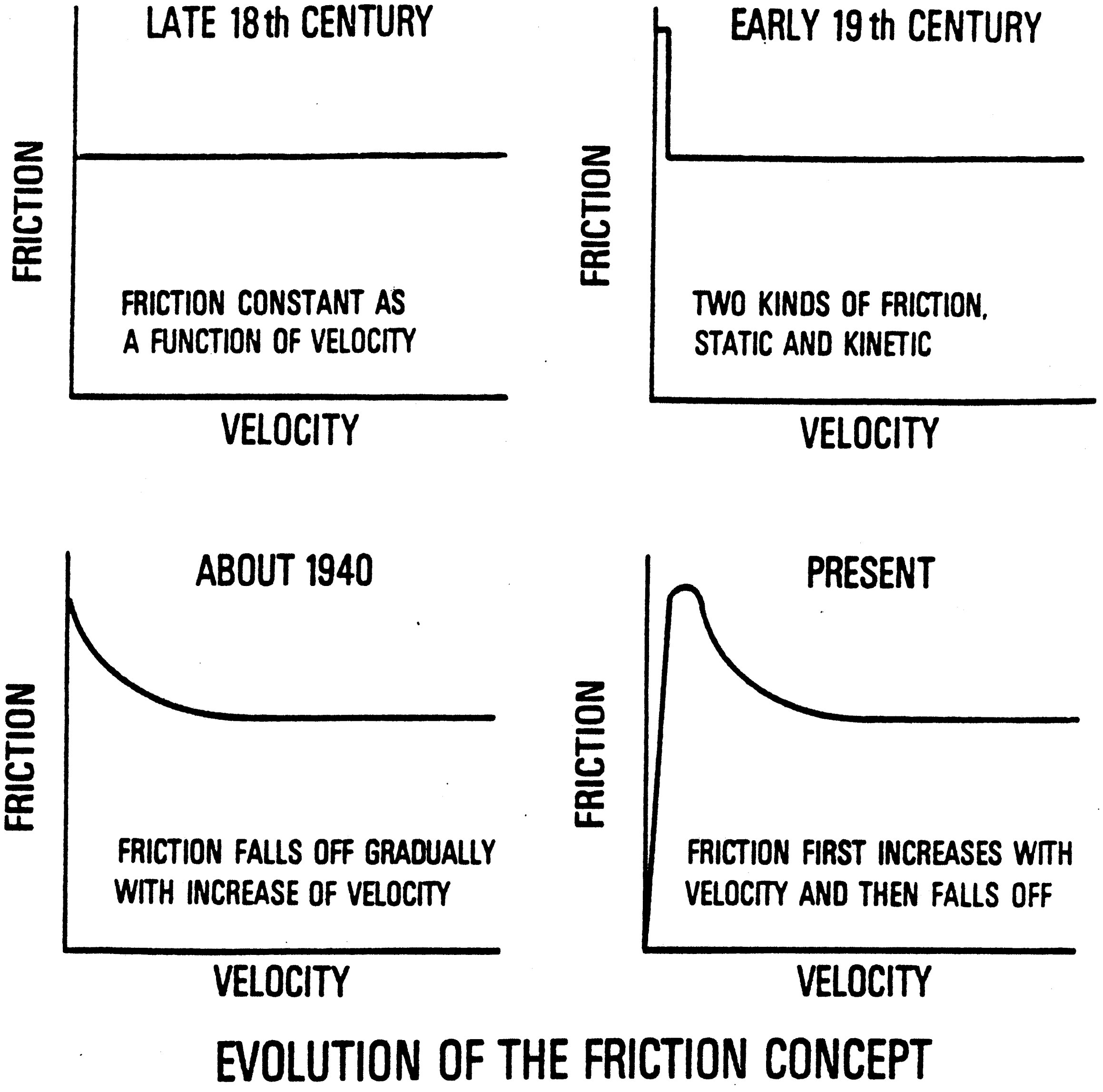


FIGURE 2. FRICTION CONCEPT RELATED TO THE VELOCITY OF SLIDING BETWEEN TWO SURFACES (IN BRUNGRABER, 1976, AS ADAPTED FROM E. RABINOWICZ, 1956).

hazard of certain shoe and floor conditions. It is these authors' opinion that with further research slip hazard levels will be defined based on expected static and dynamic friction levels, and the latter will depend on certain task requirements (i.e., slow walking, fast walking, turning, pushing or pulling carts, etc.). For the present, however, for both measurement convenience and because many combinations of variables affecting dynamic friction have not been well studied, static, or near static, friction measurement will persist for field use.

Thus the practical justification for this study is simply to assure that static friction is measured with devices with known operating characteristics. Clearly as more is known about dynamic friction and practical measurement devices are developed for estimating its magnitude under field conditions, a similiar study should be initiated.

1.3 Description of Measurement Devices Evaluated

Three different devices were evaluated in this study. Two, referred to as the Slipometer (Creativity, Inc.) and the Bigfoot (Safety Sciences) can be characterized as "towed sled" designs. The third, referred to as the Brungraber Device (Brungraber, Inc.), is an "articulated strut" design. The devices will be described in order of increasing complexity (Bigfoot, Slipometer, and Brungraber). The construction of the devices has been described in the literature before (Irvine, 1967; Brungraber and Adler, 1978; Cohen and Compton, 1982). The following descriptions will concentrate on the principle of operation, the size and weight of the apparatus, the design of the sensors, and the ease of changing the sensors.

1.3.1 Bigfoot

This device was constructed by the investigators from a specification sheet and photographs (provided by Safety Sciences, Inc.). The principle of operation is measurement of the force required to pull a sled of known weight across the floor surface. The force measurement gauge used in the device is a Chatillon (R-CAT-719-10) which retains the peak reading mechanically (see photos of Bigfoot, Figure 3). The gauge is 24 inches long and lightweight. The sled portion of the device weighs 10 pounds, and holds a sample of shoe material on the bottom to act as a sensor, measuring 4.75 inches x 3.75 inches. The sensor is attached to the sled by double-stick carpet tape, and is easily removed or changed. Operation requires manual pulling of the sled over the surface being measured. The maximum force required to begin sliding the sled is read from the "peak force" indicator on the Chatillon gauge. Unfortunately, there were no detailed instructions for operation available.

1.3.2 Slipometer

The Slipometer is often commonly referred to as the Horizontal Pull Slipometer. It was designed by Charles Irvine at Liberty Mutual Insurance Company in the mid 1960's. Like the Bigfoot, the device has two components: a force gauge and sensors mounted on a sled and a constant rate pull towing motor. The gauge is a custom Chatillon force gauge (DPP type) with a maximum reading needle on a dial indicator. It is mounted on the top of a metal sled,

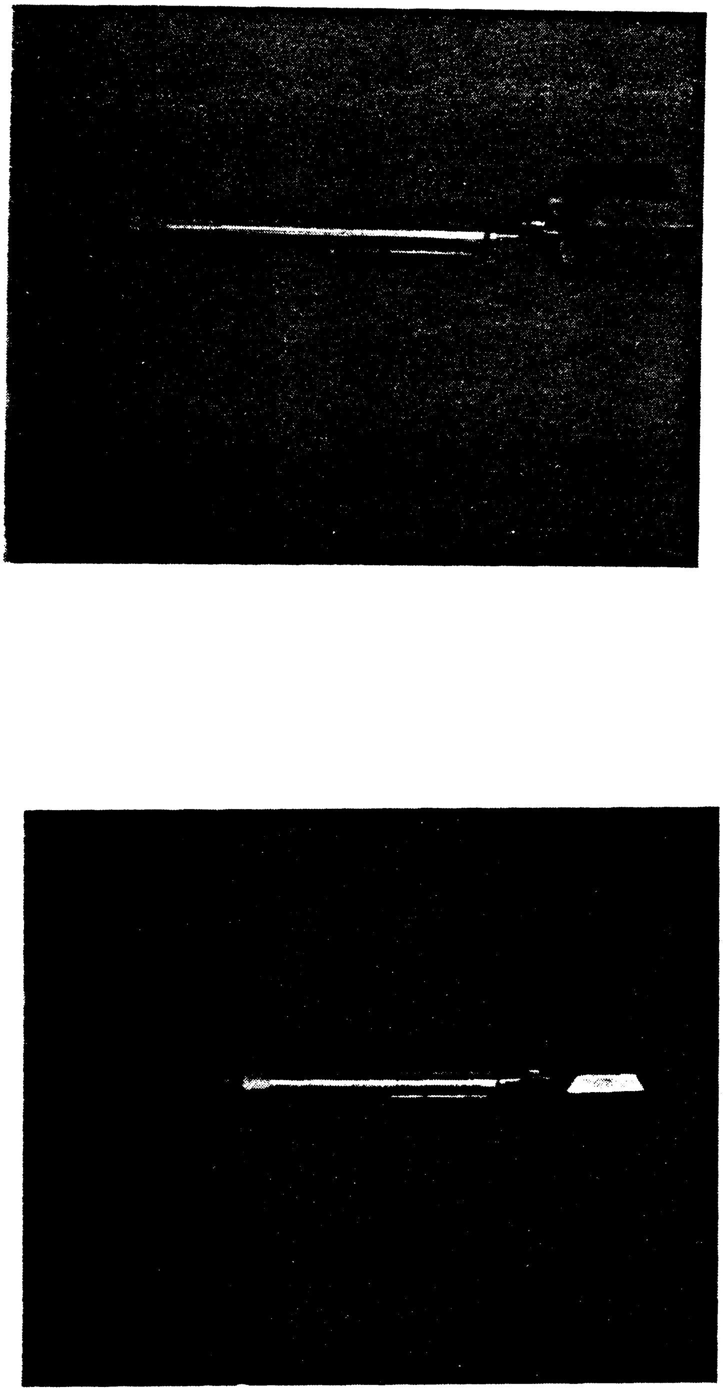


FIGURE 3. PHOTOGRAPHS OF BIGFOOT SURFACE FRICTION MEASURING DEVICE USED IN PRESENT STUDY.

the bottom of which has three 1/2 inch diameter insets 1/8 inch deep. Round plugs of shoe material are stuck into these insets to act as the sensors.

The separate pull box contains a battery-powered capstan motor attached to an external pulley. The capstan reels in a string to which the force gauge on the sled is attached. The device is depicted in Figure 4. The sled portion of the device weighs approximately 6 pounds. Both units of the device are supplied in a convenient carrying case (22" x 13" x 7") which weighs 24 pounds with device.

1.3.3 Brungraber Device

This device, designed by Robert Brungraber when he was working for the National Bureau of Standards, is the most complicated of the three devices. It is based on the articulated strut principle used by the larger James machine. The measurement gauge is a cylindrical rod which is pulled along by the articulated strut until slip occurs, at which point the gauge is grabbed by a clamping mechanism. The load on the shoe is about 12 lbs. initially. The sensor (3 inches x 3 inches) is attached to the shoe by a spring steel clip.

Figure 5 displays the design. Operation requires a load to be applied to the sensor by the articulated strut. The load slides along on horizontal rails. As it does it applies an increasing shear force and decreasing compressive load on the sensor and floor contact area. The angle of the strut where-in the sensor begins to slide is indirectly measured by a recording shaft pulled along by the load. When the sensor begins to slide a mechanical clamp

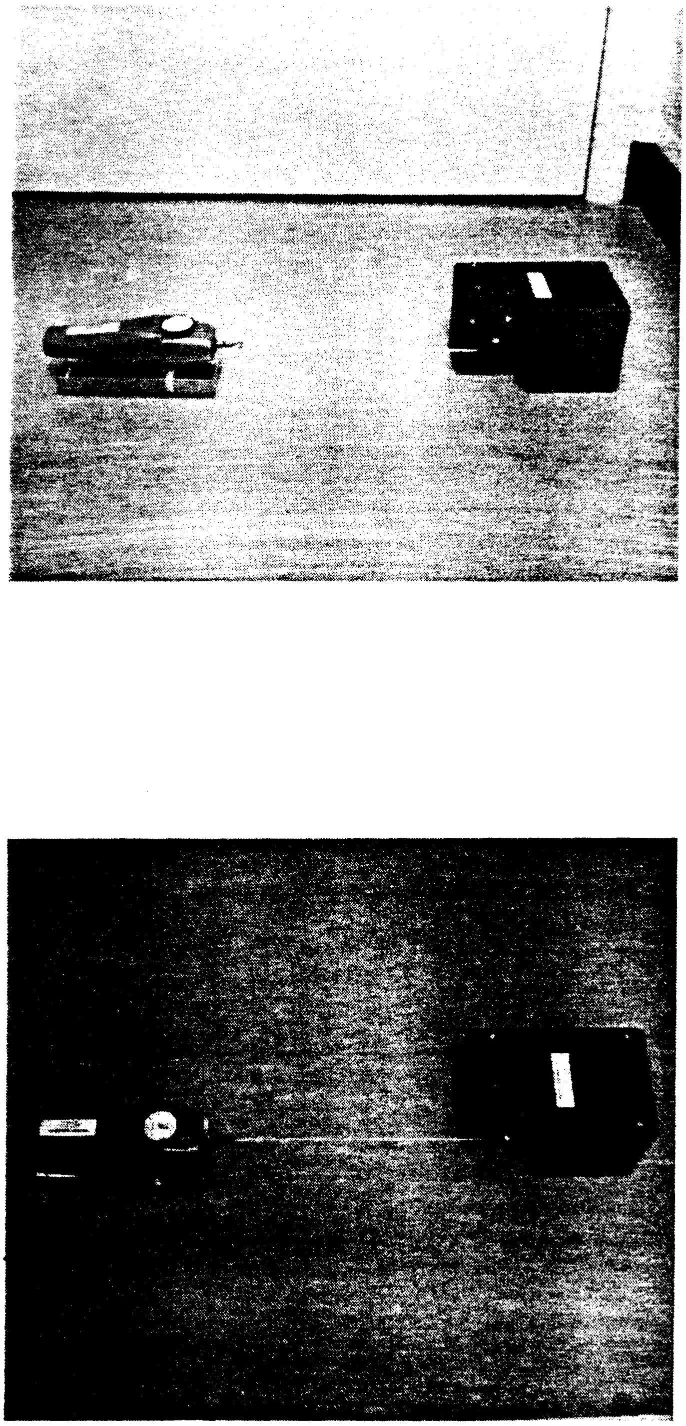


FIGURE 4. PHOTOGRAPHS OF SLIPOMETER SURFACE FRICTION MEASURING DEVICE USED IN PRESENT STUDY.

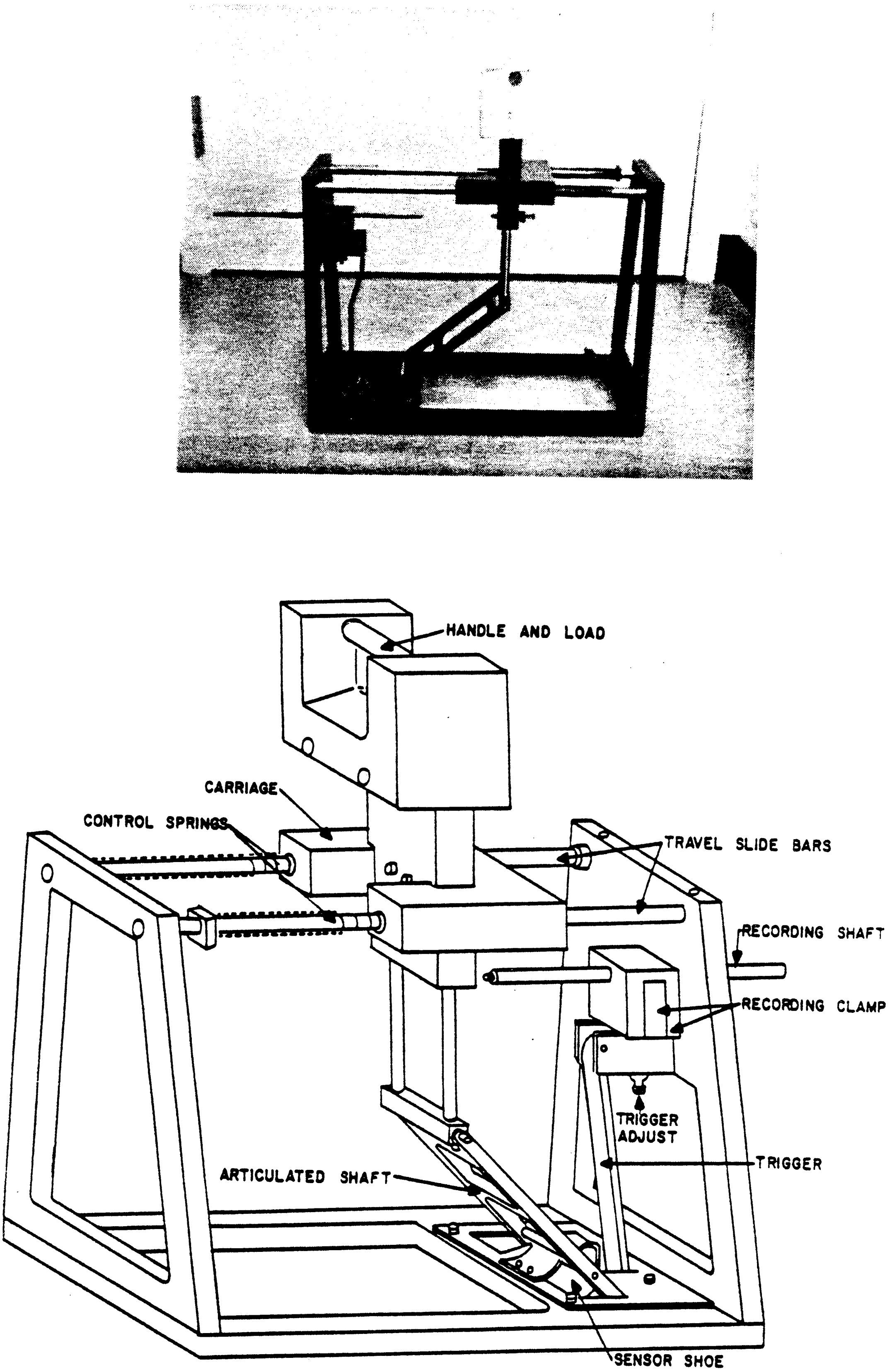


FIGURE 5. PHOTOGRAPH AND DIAGRAM OF BRUNGRABER SURFACE FRICTION MEASURING DEVICE USED IN PRESENT STUDY.

is activated which stops the recording shaft's motion so the operator can record the distance it moved just as the sensor slid on the floor. This reading is then used with a calibration graph to determine the coefficient of friction. Detailed operating instructions came with the device.

Shoe material is cut to the size of the sensor shoe (3" x 3") and stuck to its bottom with carpet tape. The entire unit is well constructed to provide necessary rigidity. This accounts for its weight of 31 pounds. It also is much larger than the other devices, measuring 24 inches high (when checked) and requires a floor area of 20 inches by 8.5 inches. A rigid carrying case is provided (21" x 23" x 9.5"). Its packaged weight is 45 pounds.

II. METHODS

Each of the three devices was evaluated in both laboratory and field (plant) studies. Sections 2.1 and 3.1 describe the methods and results of the laboratory studies. Sections 2.2 and 3.2 describe the methods and results obtained from the field studies.

2.1 Laboratory Study Methods

Three types of laboratory studies were run to determine consistency between devices, repeatability, ease of use, and accuracy. These experiments will be referred to as, 1) Main Experiment, 2) Side Experiments, and 3) Force Platform Experiments.

Consistency between devices was determined by statistically comparing the mean values of repeated measures obtained from each device under controlled conditions. Repeatability was assessed by comparing the variation in consecutive readings obtained under various standardized conditions. Ease of use was subjectively evaluated by two operators on a scale of 1 to 5 after each use, and by timing the acts of setting-up and performing measurements. Accuracy was determined by mounting each device over a Kistler Force Platform and directly comparing the COF of the device with maximum COF obtained from simultaneous measures of the normal and shear forces applied by the devices to various floor materials mounted on the force platform.

In all experiments, several general conditions were standardized. These were:

1. Shoe sample materials for the sensors were sanded between each experiment with 400 grit sand paper, using 4 four inch strokes in one direction and 4 in a direction normal to the first. The sensors were then cleaned with a brush.

2. Temperature was approximately 70° to 80° F. for all experiments.

3. Floor samples were washed and dried before each experiment. After 10 measurements the sample was wiped with a soft dry cloth to remove any loose contaminants.

4. All studies were conducted by two operators to reduce the chance of operator bias when comparing the devices.

Three shoe materials were selected on the basis of purported use in industrial settings, and to obtain a wide range of sensor conditions to evaluate the devices. The first was <u>Natural Leather</u> (sometimes called Type 1 or "Factory Leather"). This material was used in both a dry state, and a pre-soaked (for approximately three hours in water) state. It was bought in sheets that were 1/4 inch thick.

The second material was called <u>Rubber Composition</u> (a compound of rubber and clay) often used in work shoes. The sheets of this material were also 1/4 inch thick.

The third shoe material was Crepe. This material was 3/8 inch thick.

All of the materials were purchased at a shoe material distributor for many of the shoe repair facilities within a 100 mile radius of Detroit, Michigan.

Five different floor materials were used for these laboratory investigations. The five materials were: 1) vinyl tile, 2) concrete, 3) wood block, 4) steel plate, and 5) All-Grip.

The vinyl tile was bought from a retail store in 12 inch by 12 inch squares, 3/32 inches thick. The concrete was a poured and glazed floor in the laboratory which was stripped and smooth. It was partitioned into four sections measuring 9 inches x 24 inches each. The wood block surface was constructed of common oak blocks used in factory flooring glued together to make an end-grain surface measuring 10.5 inches x 7.5 inches x 1 inch thick. The wood floor surface was rough sanded. The steel plate surface came from a hot-rolled floor, was smooth and shiny, and measured 12 inches x 9 inches x 3/16 inches thick. The All-Grip sample (from Safe-Walk, Inc.) is a high friction surface of impregnated steel. The sample was 12 inches x 12 inches x 3/32 inches thick.

Not all industrial floors are dry. Each of the test instruments was tested on dry floors, waxed floors, waxed floors wet with water, waxed floors wet with a soap/water solution, and waxed floors coated with light machine oil. The wax used was Trewax Gold Label Sealer and Wax. The coats of wax were applied after the surfaces were washed and stripped. The soap used was Grime-Go (1 part per 128 water). The oil was Liquid Wrench Super Oil (L10-04). The water, oil, and soap solutions were sprayed on liberally before each set of 10 readings. Each device and shoe combination was used 10 times by each operator to check the floor conditions in the following order: 1) dry, 2) waxed, 3) waxed and wet, and 4) waxed and soapy. The data were recorded on the data sheet included in Appendix B.

Investigation of the several factors which could affect the consistency, repeatability and ease of use of each device in the laboratory required two different groups of experiments. Each will now be described.

2.1.1 Main Laboratory Experiment

Three shoe (sensor) materials (dry leather, wet leather, and rubber composition), three floor surfaces (vinyl tile, concrete, and wood block) and four different floor conditions (dry, waxed, waxed and wet, and waxed and soapy) were chosen for this major study of the three devices. Two different people operated the devices for all conditions. The paradigm was a full factorial design based on the model:

$$Y_{ijklm} = \mu + A_i + B_j + C_k + D_l + AB_{ij} + AC_{ik} + AD_{il} + BC_{jk} + BD_{jl} + CD_{kl} + E_{ijklm}$$

where A = shoe material's effect

B = floor material's effect

C = device effect

D = floor condition effect

E = error term

Y = coefficient of friction reading, and

$i = 1,2,3$; $j = 1,2,3$; $k = 1,2,3$; and $l = 1,2,3,4$.

Notice that only first order and two-factor interactions are included in the model, as higher order interactions were not believed to be of practical importance. Since 10 readings were taken for every set of conditions with each device, the total number of readings taken for this experiment was 1,080.

The resulting analysis of variance (ANOVA) was performed with all 10 recordings included to determine if consistent differences existed between the devices under the various operating conditions. The ANOVA was then repeated on the first 5 recordings and the last 5 to determine if under certain conditions the devices changed consistency. Plots of the mean values of the repeated readings for the various conditions were also prepared for visual inspection.

The repeatability of the devices was also determined by developing estimates of the standard deviations of the recordings under each experimental condition. ANOVA was used to determine if the repeatability varied between devices and conditions. Mean values of the standard deviations under the various conditions were also plotted for visual inspection.

2.1.2 Side Experiments

Four side experiments were performed to determine if specific experimental conditions affected the consistency between the devices or their repeatability. These are now described.

2.1.2a Side Experiment # 1; Concrete vs. Steel Surfaces. This experiment compared each device's performance on concrete and steel surfaces. Two shoes (wet leather and rubber composition), two floors (concrete and steel), and four floor conditions (dry, waxed, waxed and wet, and waxed and soapy) were used with the three devices. The full factorial design was again employed, using the same model as for the main experiment (except $i = 1,2$; $j = 1,2$). For the 10 replications the total number of readings was 480.

2.1.2b Side Experiment #2; Steel and All-Grip Floors. This experiment contrasted device performance on steel and All-Grip floor surfaces. Two shoes (wet leather and rubber composition), two floors, and four floor conditions (same as main experiment) were used with all three devices. The full factorial model is the same as Side Experiment #1, resulting in 480 readings.

2.1.2c Side Experiment #3; Rubber Composition and Crepe Shoes. This experiment was meant to determine device performance for rubber composition and crepe shoe materials. Besides the two shoe materials, two floors (vinyl tile and concrete) and the same four floor conditions were used with all three devices. The model remained the same as Side Experiment # 1 with 480 readings.

2.1.2d Side Experiment #4; Soapy and Oily Waxed Floors. Device performance on soapy and oily waxed floors was investigated in this experiment. Three shoes (dry leather, wet leather, and rubber composition), three floors (vinyl tile, concrete and wood block), and the two floor conditions (soapy and oily) were used with the three devices. The factorial model was the same as for the main experiment, except 1 = 1,2. The total number of readings taken was 540.

2.1.3 Accuracy Experiment

From the preceding experiments specific conditions were identified to determine the accuracy of each of the three devices. These studies provided the means to define three slipperiness levels: very slippery, medium slippery, and high friction conditions. The slippery condition chosen was produced with wet leather shoe material on waxed, wet vinyl tile. A medium slippery condition used dry leather on dry vinyl tile. The high friction condition was rubber composition shoe material on dry wood block floor material.

Since formal operating instructions for the Bigfoot were non-existent, its accuracy was examined for two different pull angles on the force gauge (0°, 45°), and two different pull speeds (slow, fast) in a separate study. A slow pull was smooth and gradual, while a fast pull was essentially a jerky motion. These latter two investigations used rubber composition shoe material and the dry wood block surface (i.e., a high friction set-up).

Analysis required paired t-tests of the maximum coefficients of friction read from each device with that measured by the Kistler Force Platform for each experimental condition. Ten consecutive readings with each device were obtained for each condition.

2.2 Field Study Methods

Six field studies were performed to determine the consistency between the devices, as well as repeatability and ease of use in typical operating environments. The areas chosen for the evaluations were reported by safety, supervisory personnel, or labor organizations as being potentially slippery. The following six field sites were evaluated.

1. Receiving dock in a laboratory building.
2. Production floor of commercial petrochemical refinery.
3. Lobby and production area of small volume printing services shop.
4. Production area in large volume graphics art print shop.
5. Production area in automotive trim manufacturing plant.
6. Production area in commercial laundry service.

The procedure for each evaluation remained the same, and is as follows:

1. The devices were transported to the field sites in individual carrying cases.

2. After discussion with on-site personnel and inspection of floor surfaces, a representative area (about 100 square inches) of the floor surface was selected.

3. The selected area was wiped with a dry clean towel to remove any loose debris or lubricants.

4. Each device was removed from its case, calibrated, and the first sensor installed.

5. Each device was then used with three different sensors (dry leather, wet leather, and combo material), with 10 trials of each material being taken.

6. The COF readings for each device/sensor combination was recorded, along with the time required to setup, perform the trials and repackage the devices. Comments were also noted about the ease of use on the surface area, and how well the device performed under the specific circumstances. The data were recorded on the data sheet included in Appendix B.

III. RESULTS

3.1 Laboratory Study Results

The results from both the main laboratory experiment and the four smaller side experiments are presented in this section. The results are presented as they relate to the following evaluation criteria:

1. Consistency between measurement devices.

2. Repeatability of each device.

3. Accuracy as determined by force platform measurements.

4. Ease of use of each device.

3.1.1 Consistency Between Measurement Devices

Consistency between the measurement devices was determined by comparison of the mean values obtained from 10 consecutive readings with each device under controlled conditions as described in the Methods Section. Analysis of variance of the means for the main experiment is shown in Table I. Statistical significance was found for both individual and paired factors at a level of less than 0.001. This is to be expected with so many repeated, relatively consistent measurements. As would be expected, the greatest effect on the COF data was attributable to the floor surfaces and how they were prepared (i.e.,

TABLE 1: ANOVA RESULTS OF MAIN EXPERIMENT

Factors	d.f.	Mean Squar	F ratios
Shoe Material	2	1.92	198
Floor Material	2	2.88	297
Measurement Device	2	3.07	317
Floor Preparation (dry, wet, waxed)	3	0.12	12
Shoe & Floor Interaction	4	0.89	91
Shoe & Measurement Device Interaction	4	0.22	23
Shoe & Floor Preparation Interaction	6	2.41	248
Floor & Measurement Device Interaction	4	0.18	18
Floor & Floor Preparation Interaction	6	0.34	35
Measurement Device & Floor Preparation Interaction	6	0.13	14
Residual Error	1040	$0.97 \times 10^{-}$	

dry, wet, waxed, or soaped). This interaction effect accounted fo 9% of the total variance in the data. Unfortunately, the next most importan actor was which device was used. This accounted for over 12% of the varianc n the data, which was slightly more than the 11% attributable to the flo surfaces alone. The shoe material used in the sensors accounted for only 8 f the total variance in the data.

These findings were repeated when only the first five readin were used in the analysis and when the last five readings were used. The af t of the devices on COF data is particularly disturbing because it indicate hat the devices are <u>not</u> comparable, and may be subject to certain biases i heir ability to determine the relative slipperiness of various floors. e mean values for the coefficients of friction are plotted in Figure 6. inspection this figure shows that the mean values are consistently different. hen compared across <u>all</u> experimental conditions the following mean val , including the side experiments, resulted:

Device:	Mean COF:
Slipometer	0.77
Big Foot	0.69
Brungraber	0.59

The high readings for the Slipometer were particularly notic le when the floor was wet and a leather sensor was used. These mean value re plotted separately in Figure 7. Apparently the time delay between the sen being set-down on the wet floor and the string applying shearing force i ufficient

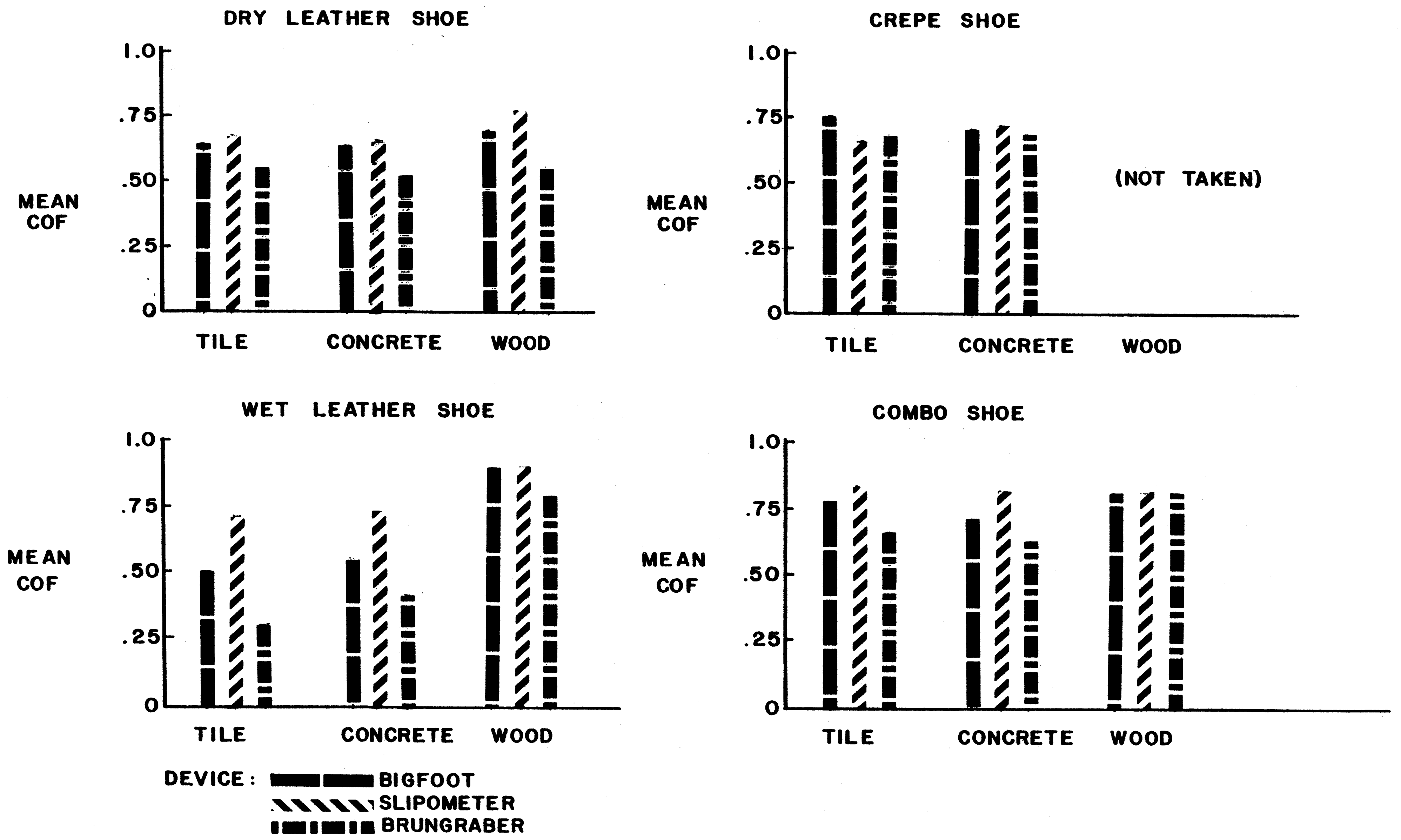
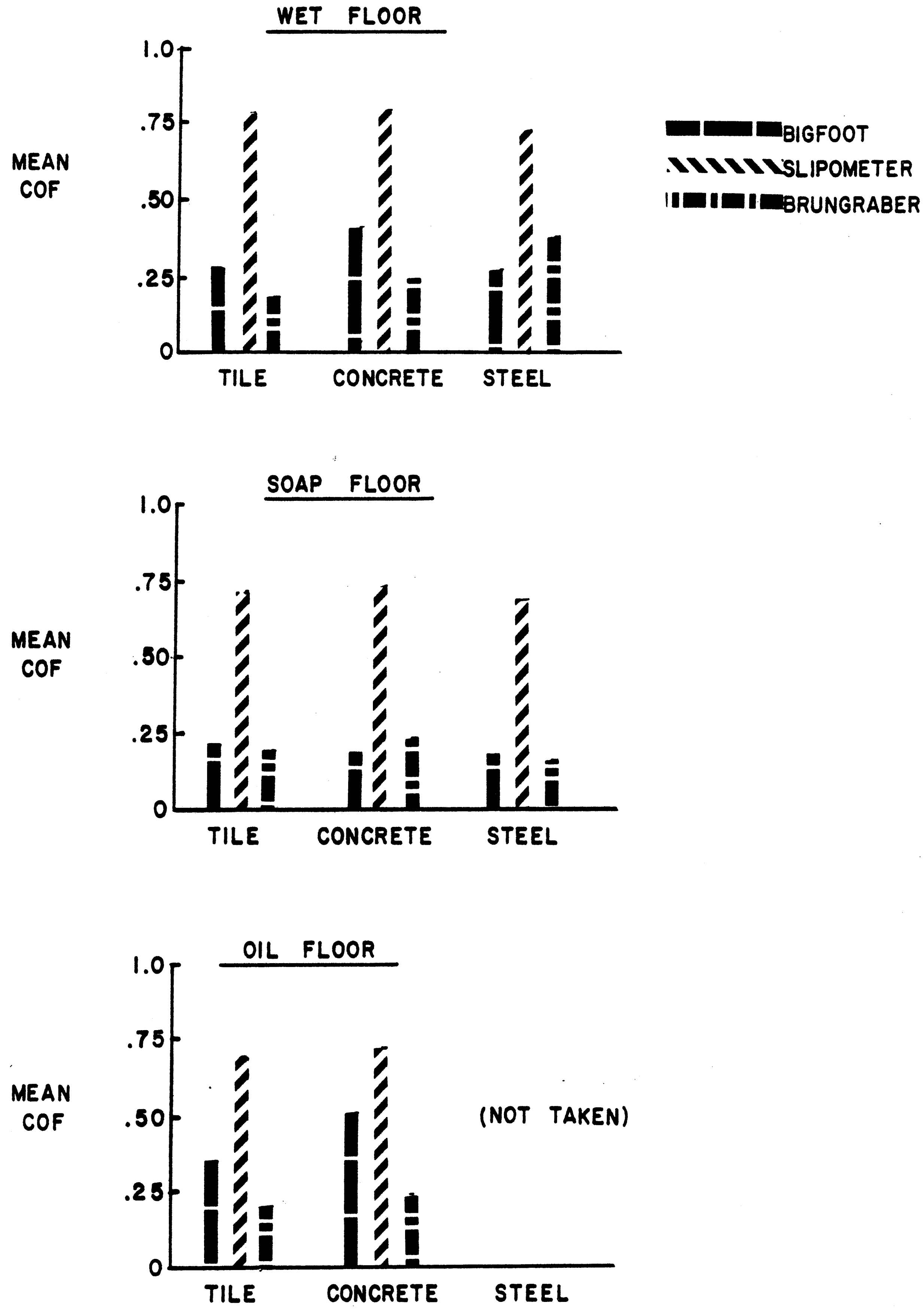


FIGURE 6: MEAN COF RESULTS FOR DIFFERENT DEVICES, SHOE AND FLOOR MATERIALS OVER ALL FLOOR PREPARATION CONDITIONS



WET FLOOR

SOAP FLOOR

OIL FLOOR

FIGURE 7. MEAN COF RESULTS FOR WET LEATHER SHOES ON WET, OILED AND SOAPY SMOOTH FLOORING

to allow adhesion to develop when the Slipometer is used. This time delay is critical, particularly with wet flooring and leather, as commented on earlier by both James (1979) and Brungraber (1976).

In using the manual Big Foot device in this study, force was applied as soon as the sensor touched the floor, thus reducing adhesion. Unfortunately the Big Foot device has no means by which the timing can be controlled when wet conditions are measured and thus large operator errors could be expected.

The Brungraber device controls the time delay to some extent, since the sensor is held mechanically above the floor until the weight which activates the device is released. As soon as the weight drops it forces the sensor against the floor, and then steadily increases the shear force until slip occurs. The time period for the Brungraber measurement would appear to better approximate normal walking relative to the other two devices; the average time of contact before slip was .78 seconds, as read from the force platform results.

3.1.2 Repeatability of Each Device

The standard deviation of the variation in repeated readings was computed for each device/shoe/floor condition. ANOVA of the resulting values disclosed no systematic affect on the repeatability, though shoe material did create an affect (particularly with the combo material having the most repeatability) which was nearly statistically different at $\alpha < 0.01$ level. The mean values of the standard deviations for the various test conditions are shown in Figure 8 from the main experiments. In general, all devices appear to be able to repeat

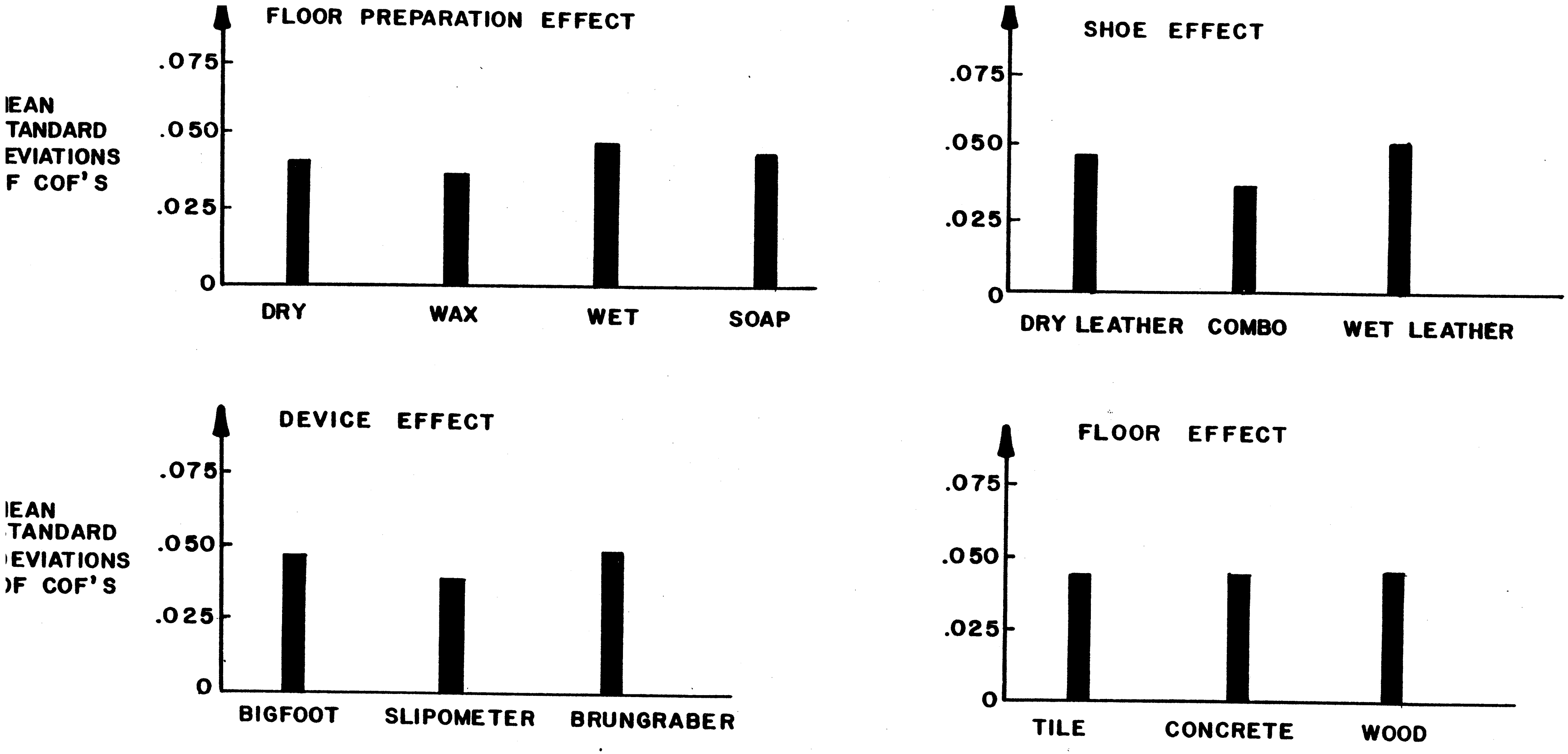


FIGURE 8. MEANS OF THE STANDARD DEVIATIONS OBTAINED FROM TEN CONSECUTIVE READINGS FOR VARIOUS EXPERIMENTAL CONDITIONS IN MAIN EXPERIMENT

most readings well within ± 10% of the mean, with combo shoe material providing the most consistent readings.

An evaluation of whether the repeatability varied during the taking of the 10 consecutive readings was performed. It revealed no major changes in repeatability during the tests, though the Big Foot appeared to be more consistent after the first few readings, while the Brungraber device became slightly more inconsistent after a few readings. The Slipometer repeatability did not change with repeated readings.

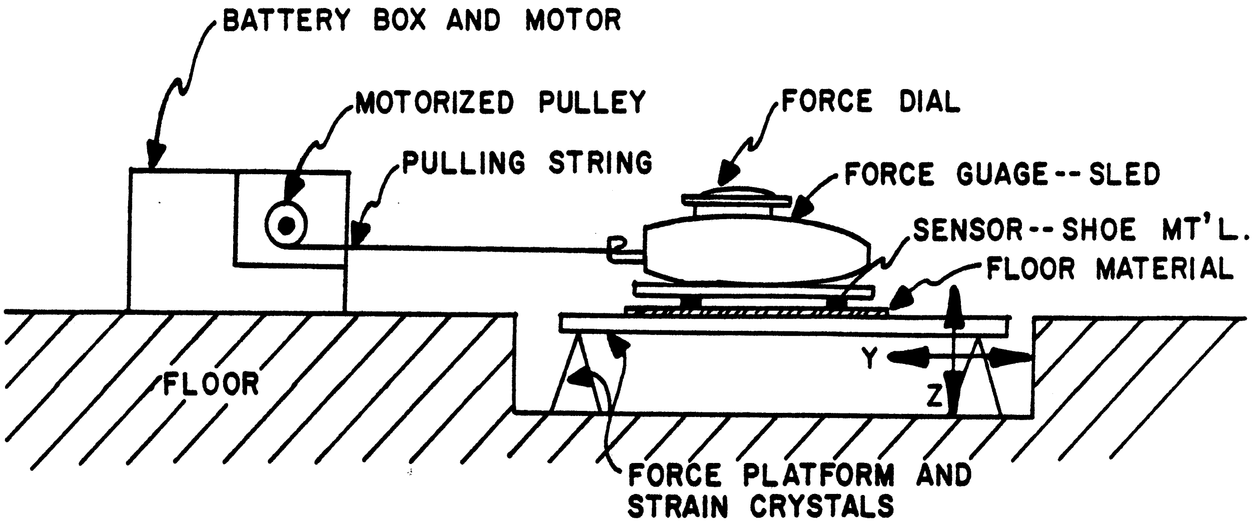
3.1.3 Accuracy of Devices

Recall from the Methods section that accuracy was determined by comparing 10 consecutive COF readings of each device with the maximum COF determined from force platform measurements of the shear and normal forces produced by the devices during the trials. Figure 9 depicts the test setup and the method of determining the maximum COF from the force platform data.

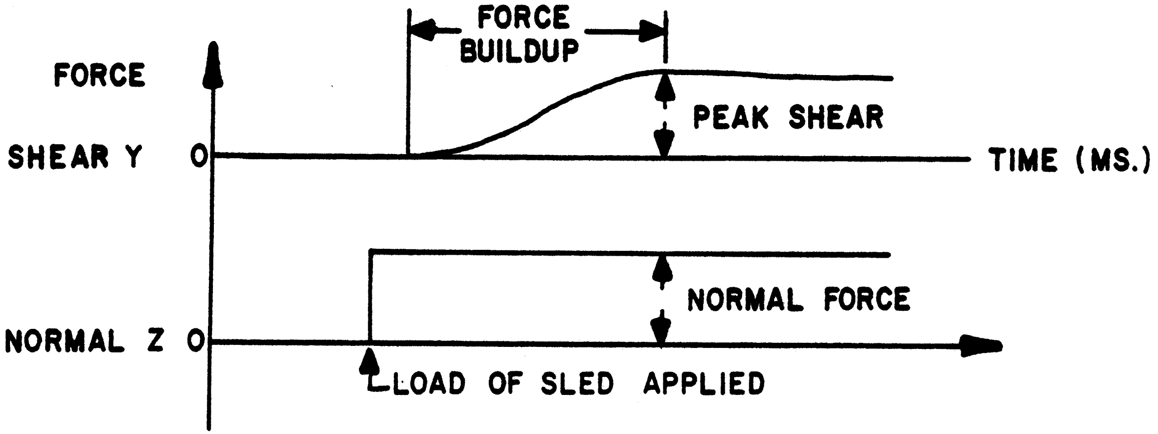
The maximum COF values from the force platform were paired with the COF values determined from each device. Mean and standard deviations were computed for the 10 trials with each device under the following experimental conditions:

1. Very Slippery - Wet leather shoe on waxed and wet vinyl tile.

2. Medium Slippery - Dry leather shoe on dry vinyl tile.



SCHEMATIC OF TEST SETUP FOR SLIPOMETER ON FORCE PLATFORM. BIGFOOT AND BRUNGRABER DEVICES SETUP IN SIMILAR MANNER WITH ONLY SENSORS IN CONTACT WITH FLOOR MATERIAL ON FORCE PLATFORM.



$$\text{COF} = \frac{\text{PEAK SHEAR FORCE}}{\text{NORMAL FORCE}}$$

FIGURE 9. FORCE PLATFORM COF ESTIMATION PROCEDURE

3. High Friction - Rubber composition shoe on wood block floor.

The mean COF values from the three devices and the force platform are plotted for comparison in Figure 10. The paired differences are depicted in Table 2 along with the error probability levels. In general, the standard deviations of the 10 readings from both the devices and the force platform values were small (i.e., below 0.07 COF), and thus the t tests of differences in the mean values plotted in Figure 10 are significant. From a practical standpoint the COF values from the devices were comparable to those computed from maximum shear and normal force data obtained with the force platform.

Two exceptions, however, are worth noting. As disclosed earlier, the Slipometer when used with wet leather and vinyl flooring appears to be susceptible to adhesion. Adhesion results in exceptionally high peak "breakaway" friction, sometimes referred to as "sticktion". Because of the compliance of the pull string and force gauge spring and the inertia in the system a sudden jerking action results, and the maximum force indicator mounted on the sled records a reading which is higher than the actual shear force at the contact surfaces. In short, under these conditions the Slipometer reads high.

The second exception worth noting is that the Brungraber device was consistently lower in its COF estimates than the force platform estimates. Recall that the Brungraber device generally produced COF estimates that were 0.1 to 0.18 units lower than the other two devices when compared across many different conditions (see Section 3.1). The force platform estimates appear to

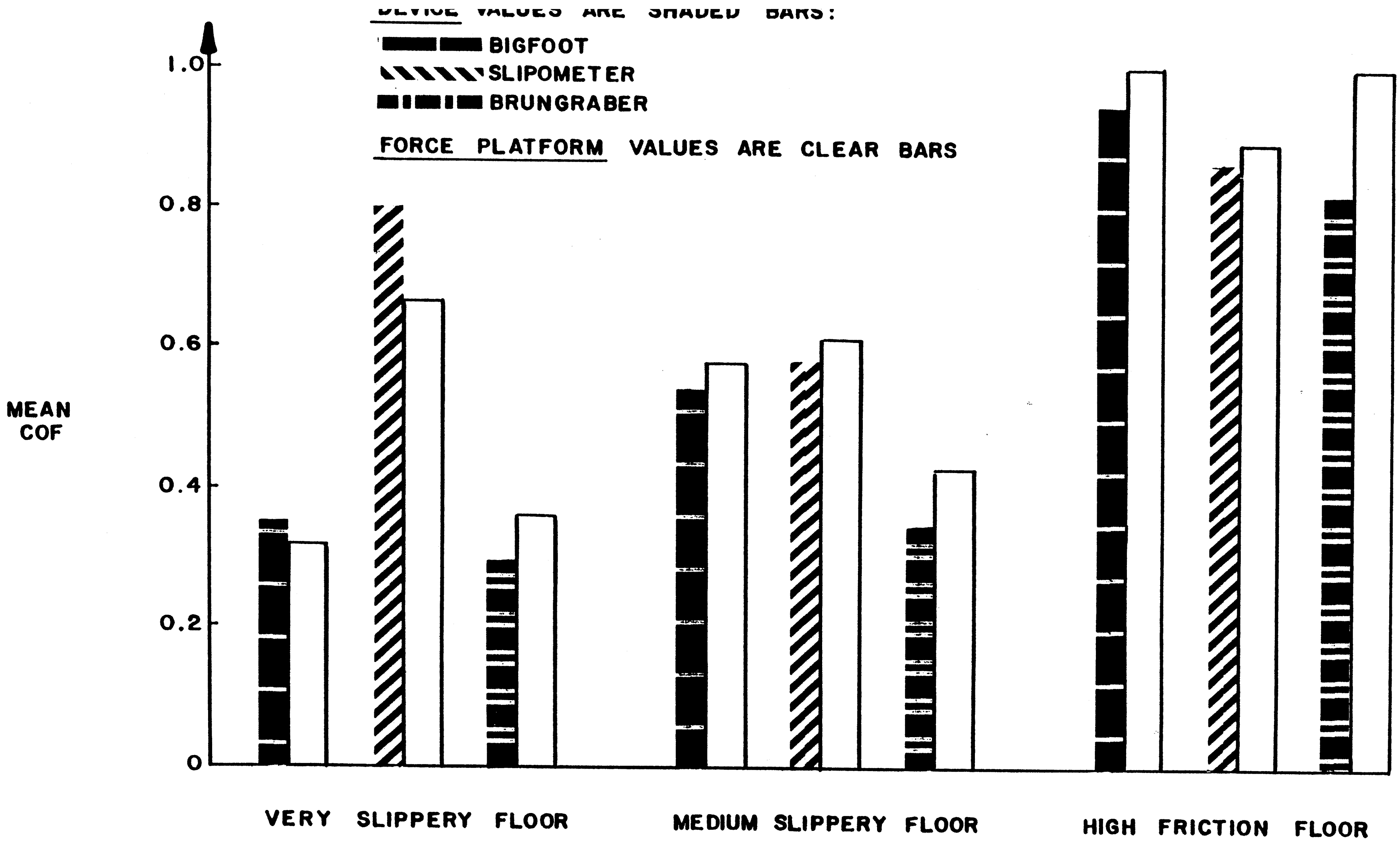


FIGURE 10: COMPARISON OF DEVICE MEAN ESTIMATES OF COF AND FORCE PLATFORM MAXIMUM COF VALUES

TABLE 2: COMPARISON OF MEAN DIFFERENCES BETWEEN THE DEVICES AND FORCE PLATFORM ESTIMATES OF THE COF FOR THREE LEVELS OF SURFACE FRICTION

Experimental Condition	Device	Mean Differences in COF (Device Mean-Force Pl. Mean)	Max.	Probability
Very Slippery	BF	+0.035		0.005
	SM	+0.125		0.005
	BG	-0.078		0.005
Medium Slippery	BF	-0.034		0.005
	SM	-0.026		0.050
	BG	-0.077		0.005
High Friction	BF	-1.116		0.005
	SM	-0.036		0.010
	BG	-0.216		0.005

confirm that the Brungraber device used in this study was not properly calibrated, as the friction force increased the bias error increased, as depicted in the mean value differences depicted in Table 2. It is not clear why such a bias should develop, but it raises a question regarding the need to have some method by which the calibration of this device can be checked periodically against several standard sensor/floor materials.

Though the Bigfoot compared very well with the force platform readings, it was believed to be susceptible to error if not carefully operated. In specific, adhesion on wet material must be avoided by applying a pull force to the sled/sensor at the instant it is set down on the floor surface. Also, if the sled is pulled too fast (i.e. jerked), the compliance and inertia of the device could result in a COF reading higher than that at the contact surfaces. Lastly, the angle of pull on the sled could vary the normal and shear forces on the sled, and hence raise the recorded COF above that at the contacting surfaces. These limitations were documented in a set of experiments using the force platform. A slow and fast pull force was administered 10 times each to the sled after it had set on wet vinyl (with a wet leather sensor) for a few seconds. Also, the pull force was repeated 10 times each with a horizontal and 45° angle, using a high friction surface. The results are shown in Table 3. These confirm that the Bigfoot is highly susceptible to operator technique. Our suggested operating instructions for the Bigfoot are detailed in Appendix A.

TABLE 3: COMPARISON OF BIGFOOT AND FORCE PLATFORM COF VALUES WITH DIFFERENT OPERATING METHODS

Experimental Condition	Operating Method	Mean COF Values Device	Mean COF Values Force Platform
Very Slippery	Slow Pull	0.31	0.29
	Fast Pull	0.58	0.22
Medium Slippery	Horizontal Pull	0.97	1.09
	45° Pull	0.76	0.68

3.1.4 Ease of Use Results

Two types of data were gathered regarding the ease of using each of the devices. First, various ergonomic and operating characteristics were identified and subjectively rated on a 1 (poor) to 5 (good) scale. These are presented in Table 4.

The second type of evaluation included timing the use and setup/repacking of each device, both in the laboratory and field. Table 5 depicts the resulting mean time values for 40 consecutive trials with each device, including sanding and cleaning sensors after 10 trials. A second person wrote down the readings verbally given by the device operator after each trial. These sets of 40 trials were repeated six times for each device. The range of times for each set of trials is given in the last column.

TABLE 5: PERFORMANCE TIME VALUES FROM USE OF DEVICES IN LABORATORY EVALUATIONS

Device	Mean Time for 40 Trials (min)	Mean Time Per Trial (min.)	Range of Times for 40 Trials (min.)
Bigfoot	7.5	0.19	5.5-10.0
Slipometer	15.3	0.38	13.0-20.0
Brungraber Device	8.2	0.20	6.0-10.0

In general, none of the three devices were found to be extremely difficult to use in the laboratory. The Slipometer does require additional time to operate due to the slow application of force through the motorized

TABLE 4: SUBJECTIVE RATINGS OF VARIOUS ERGONOMIC AND OPERATING CHARACTERISTICS OF EACH DEVICE

Characteristic	Device	Ratings (poor) 1	2	3	4	(good) 5
Setting-up to use (included installing sensors, calibration check, positioning in test area)	BF					●
	SM			●		
	BG			●		
Readability of scales (and graph of BG device)	BF				●	
	SM			●		
	BG			●		
Not sensitive to irregulatiry in floor surfaces or curvatures	BF					●
	SM			●		
	BG			●		
Not influenced by operator methods while obtaining measurement	BF			●		
	SM				●	
	BG					●
Ease of moving device from one adjacent surface location to another	BF					●
	SM				●	
	BG					●
Ease of packing/unpacking and carrying to a distant location	BF					●
	SM					●
	BG			●		

drive system. It also is difficult to prepare and mount the small sensors, plus the dial scale requires careful interpolation when reading high friction forces. Its small sensor "feet" also were found to "hang-up" in the cracks on the wood block flooring.

The Bigfoot's major disadvantage appears to be its sensitivity to the technique used by the operator in applying force to the sled, as commented on in the previous subsection. Other than this it is a simple and easy to use device.

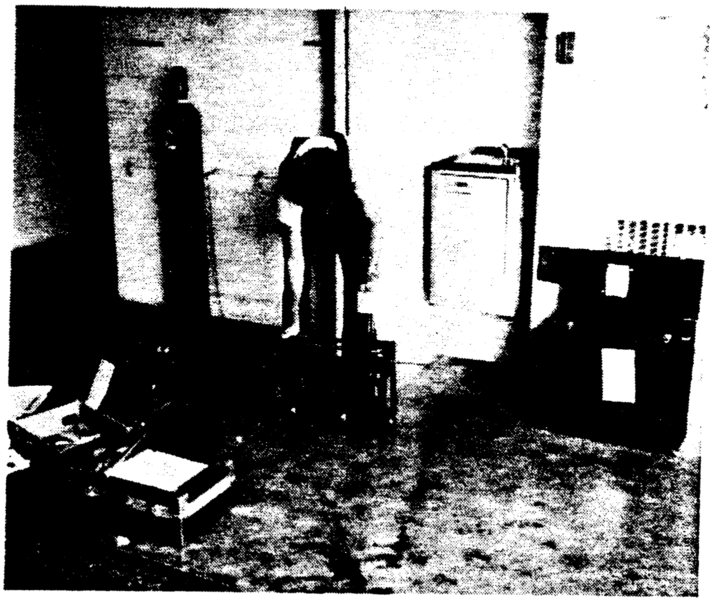
The Brungraber device proved to be more difficult to use than expected. Though the actual performance time is fast (almost the same as the Bigfoot) checking and adjusting its calibration with a clearance gauge, manuevering the heavy weight of the fixture to install new sensors, reading a small diameter slider bar with few numbered divisions, and packing/unpacking and carrying its 45 pound weight are major disadvantages.

3.2 Field Study Results

What follows are descriptions of the six sites visited and compilations of the data obtained at each site. Photographs of each site are presented, and the floor surfaces selected for the study are described in detail. Device performance is summarized for each shoe/floor combination, and the average timing required for particular phases of operation is tabulated. Finally, the results for each shoe/floor combination are averaged over the three devices. This section concludes with a summary of the results from the six field studies, averaged for each of three test instruments.

3.2.1 Receiving Dock

A. Photographs



B. Floor Description: Laboratory loading dock and entrance area, dry concrete with wax, light traffic, smooth surface.

C. Device Performance (Shoes: 1 = Dry Leather, 2 = Combo, 3 = Wet Leather)

1. Bigfoot

Shoe	Mean	S.D.
1	.376	.038
2	.699	.018
3	.767	.055
Average	.614	

Average Timing (minutes)		
Set-Up & Calibrate	Change Shoes	Readings
2.0	2.75	1.0

2. Slipometer

Shoe	Mean	S.D.
1	.511	.038
2	.809	.026
3	.648	.044
Average	.656	

Average Timing (minutes)		
Set-Up & Calibrate	Change Shoes	Readings
2.0	1.33	2.33

3. Brungraber

Shoe	Mean	S.D.
1	.319	.029
2	.556	.046
3	.310	.033
Average	.395	

Average Timing (minutes)		
Set-Up & Calibrate	Change Shoes	Readings
4.0	1.0	.9

D. Combined results stratified by shoe sensor (Means and S.D.'s averaged over 3 devices).

Shoe	Mean	S.D.
1	.402	.035
2	.688	.030
3	.575	.044

3.2.2 Petrochemical Refinery

A. Photographs

Floor # 1

Floor # 2

Floor # 3

B. Floor Descriptions

1. Concrete impregnated with oil.
2. Concrete impregnated with oil, with water puddles.
3. Diamond pattern deck plate impregnated with oil.

C. Device Performance

1. Bigfoot

Floor	Shoe	Mean	S.D.
1	1	.650	.056
	2	.734	.053
	3	.760	.039
2	3	.685	.084
3	3	.581	.065
Average		.614	

Average Timing (minutes)	
Set-Up & Calibrate	Readings
1.83	1.22

2. Slipometer

Floor	Shoe	Mean	S.D.
1	1	.812	.081
	2	.751	.041
	3	.764	.035
3	3	.844	.052
Average		.793	

Average Timing (minutes)	
Set-Up & Calibrate	Readings
1.25	2.42

3. Brungraber

Floor	Shoe	Mean	S.D.
1	1	.579	.039
	2	.755	.031
	3	.734	.049
2	3	.685	.084
3	3	.537	.030
Average		.651	

Average Timing (minutes)	
Set-Up & Calibrate	Readings
1.67	.92

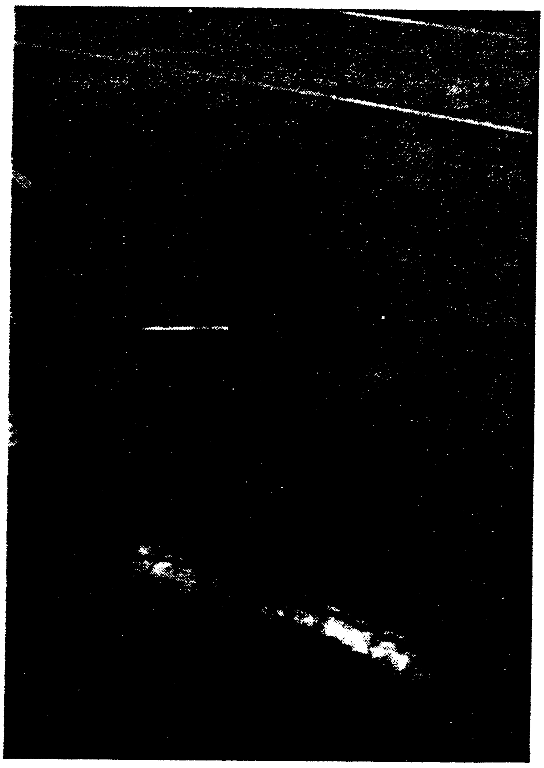
D. Combined results stratified by shoe and floor (averaged Means and S.D.'s).

Floor	Shoe	Mean	S.D.
1	1	.680	.059
	2	.747	.042
	3	.753	.041
2	3	.685	.084
3	3	.633	.049

3.2.3 Printing Services

A. Photographs

Floor # 1



Floor # 2

B. Floor Descriptions

1. Vinyl tile, waxed to a high gloss, slick with silicon dust before ragging off.
2. Ceramic tile (6" x 6"), waxed, wet with water, heavy traffic.

C. Device Performance

1. Bigfoot

Floor	Shoe	Mean	S.D.
1	1	.367	.038
	2	.551	.054
	3	.763	.090
2	1	.540	.101
	2	.700	.043
	3	.552	.103
Average		.579	

Average Timing (minutes)

Set-Up & Calibrate	Change Feet	Readings
1.0	2.1	1.65

2. Slipometer - No Readings Because Battery Shorted Out

3. Brungraber

Floor	Shoe	Mean	S.D.
1	1	.320	.014
	2	.366	.044
	3	.490	.032
2	1	.636	.018
	2	.736	.030
	3	.407	.104
Average		.395	

Average Timing (minutes)		
Set-Up & Calibrate	Change Feet	Readings
.875	1.45	1.4

D. Combined results stratified by shoe and floor (averaged Means and S.D.'s).

Floor	Shoe	Mean	S.D.
1	1	.344	.026
	2	.459	.049
	3	.627	.061
2	1	.588	.060
	2	.718	.037
	3	.480	.104

3.2.4 Graphic Arts Print Shop

A. Photographs

B. Floor Description: End-grain wood block with oil and tar impregnated, rough grain.

C. Device Performance

1. Bigfoot

Shoe	Mean	S.D.
1	.393	.049
2	.743	.045
3	.731	.050
Average	.622	

Average Timing (minutes)

Set-Up & Calibrate	Change Feet	Readings
1.0	1.63	2.1

2. Slipometer

Shoe	Mean	S.D.
1	.490	.077
2	.801	.028
3	.823	.072
Average	.705	

Average Timing (minutes)

Set-Up & Calibrate	Change Feet	Readings
2.5	2.9	3.75

2. Brungraber

Shoe	Mean	S.D.
1	.369	.037
2	.688	.092
3	.617	.049
Average	.558	

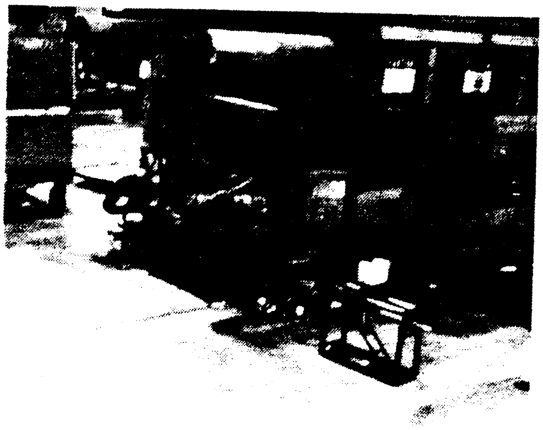
Average Timing (minutes)		
Set-Up & Calibrate	Change Feet	Readings
1.4	1.6	1.6

D. Combined results stratified by shoe (averaged Means and S.D.'s).

Shoe	Mean	S.D.
1	.417	.054
2	.744	.055
3	.572	.057

3.2.5 Automotive Trim Shop

A. Photographs



B. Floor Descriptions

1. Waxed concrete with oil and dust before ragged off.
2. Concrete coated with limestone resin hardener, then painted.

C. Device Performance

1. Bigfoot

Floor	Shoe	Mean	S.D.
1	1	.545	.043
	2	.785	.033
	3	.931	.047
2	1	.522	.054
	2	.787	.039
	3	.855	.269
Average		.738	

Average Timing (minutes)		
Set-Up & Calibrate	Change Feet	Readings
1.25	2.3	1.5

2. Slipometer - Failed to Function Due to Battery Short

3. Brungraber

Floor	Shoe	Mean	S.D.
1	1	.430	.058
	2	.630	.058
	3	.564	.086
2	1	.394	.063
	2	.698	.024
	3	.639	.052
Average		.559	

Average Timing (minutes)

Set-Up & Calibrate	Change Feet	Readings
.88	2.2	1.67

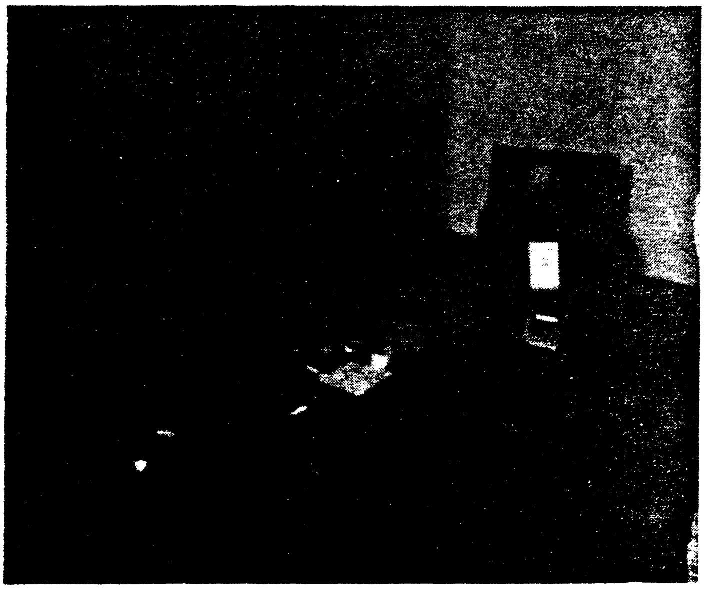
D. Combined results stratified by shoe and floor (averaged Means and S.D.'s).

Floor	Shoe	Mean	S.D.
1	1	.488	.051
	2	.708	.046
	3	.748	.067
2	1	.458	.059
	2	.743	.032
	3	.747	.161

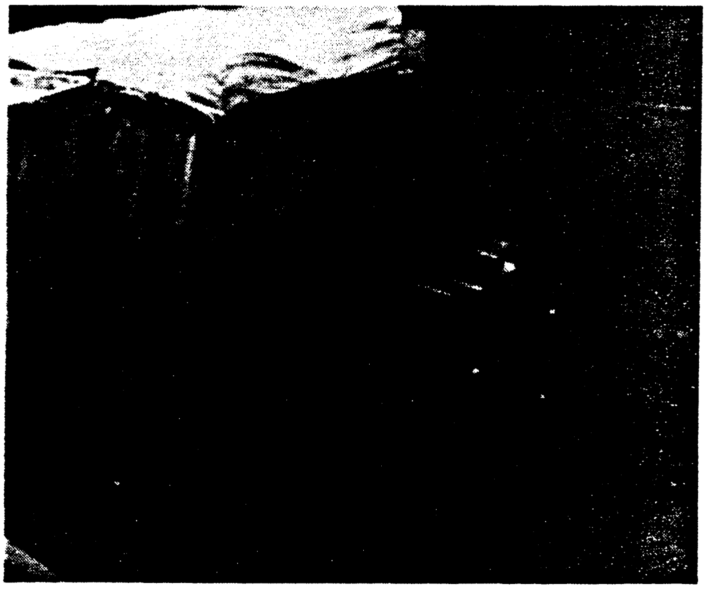
3.2.6 Commercial Laundry Service

A. Photographs

Floor # 1



Floor # 2



B. Floor Descriptions

1. Painted concrete, waxed and gritty, light traffic.
2. Waxed concrete, heavy traffic.

C. Device Performance

1. Bigfoot

Floor	Shoe	Mean	S.D.
1	1	.356	.045
	2	.738	.034
	3	.896	.067
2	1	.368	.031
	2	.731	.043
	3	.949	.037
Average		.673	

Average Timing (minutes)	
Set-Up & Calibrate	Readings
1.6	1.2

2. Slipometer

Floor	Shoe	Mean	S.D.
1	1	.332	.019
	2	.773	.023
	3	.663	.041
2	1	.457	.038
	2	.741	.022
	3	.715	.029
Average		.614	

Average Timing (minutes)	
Set-Up & Calibrate	Readings
1.4	2.8

3. Brungraber

Floor	Shoe	Mean	S.D.
1	1	.302	.030
	2	.597	.021
	3	.656	.034
2	1	.380	.029
	2	.743	.017
	3	.784	.010
Average		.577	

Average Timing (minutes)	
Set-Up & Calibrate	Readings
.85	1.4

D. Combined results stratified by shoe and floor (averaged Means and S.D.'s).

Floor	Shoe	Mean	Mean
1	1	.330	.031
	2	.688	.026
	3	.738	.047
2	1	.402	.033
	2	.738	.027
	3	.816	.025

3.2.7 Summary of Field Study Results

A. Device Performance

1. Over all field conditions and all shoes (averaged Means and S.D.'s).

Device	Mean	S.D.	N
Bigfoot	.642	.059	29
Slipometer	.683	.042	16
Brungraber	.544	.041	28

IV. Conclusions and Recommendations

1. The three devices studied measure friction under static conditions, and with relatively slow force buildup times compared to that which occurs during normal walking. It can be expected that in some tasks (e.g., rapid walking, turning, or when pushing and pulling carts) the foot may contact the floor with a velocity and shear force of a magnitude which would exceed the force of friction predicted by these devices, thus presenting an unknown slip hazard.

Recommendation: Research is needed to determine the precise foot velocity and shear forces that develop during common industrial activities, so as to be able to specify the magnitude of "correction" in the static friction estimates needed to assure a low slip potential in such activities.

2. There appears to be some limited conditions where-in friction forces may actually increase with velocity of contact, and, therefore, static friction measurements would over-estimate the degree of hazard.

Recommendation: An effort is needed to develop a surface friction measuring device which is capable of both static and dynamic friction measurements and meets the field-use criteria discussed in this report.

3. The measurement of friction of wet surfaces introduces a potential large error (over-estimate due to adhesion) if the sensor (particularly leather) remains in contact with the surface before force is applied.

Recommendation: The measuring devices must control the length of the delay time between surface/sensor contact and shear force application. Of the three devices evaluated, the Brungraber device is the best in this regard.

4. Though the measurement of static friction is simple in concept, many variables can effect the accuracy of such measurements in the field.

Recommendation: The use of two "standard friction" measuring surfaces (one low and one medium friction) with specific sensors should be developed to assure calibration of the devices under field conditions, and later comparisons of measurements from different devices and conditions.

5. In general, even though a particular floor surface yields a low static COF, our results show enough variation in response with type of shoe material that it may be possible to change footwear instead of the floor surface to control the slip risk.

Recommendation: More testing needs to be done with commercially available work shoe soles on slippery industrial floors.

6. The desire to obtain field data on surface friction dictates that measuring devices meet strict ergonomic criteria to reduce operator errors and improve his/her performance. In particular, the Bigfoot was the simplest and least time consuming device to use, but had the potential for the largest operator induced errors. The Brungraber device was the least prone to operator errors, but was more difficult to transport, set up and assure calibration.

The Slipometer was not as prone to operator errors as the Bigfoot, but was more time consuming to use than the other two devices by a factor of two.

Recommendation: A development effort is necessary to improve the present devices or design a new device which would meet the ergonomic and performance criteria stated in this report.

BIBLIOGRAPHY

1. Amontons, M. "De la Resistance Causee dans les Machines." Histoire de l'Academie Royale de Sciences, 1699, p. 206.

2. Brungraber, R. J. "An Overview of Floor Slip-Resistance Research with Annotated Bibliography." NBS Technical Note 895, National Bureau of Standards, Washington, D. C., January 1976.

3. Brungraber, R. J., and Adler, S. C. "Technical Support for a Slip-Resistance Standard Walkway Surface: Measurement of Slip-Resistance." ASTM STP 649, Anderson and Senne, eds., ASTM, 1978, pp. 40-48.

4. Cohen, H. H., and Compton, D. M. J. "Collection and Analysis of Work Surface Accident Profile Data." Submitted for publication to Professional Safety, 1982.

5. Coulomb, C. A. "Theory of Simple Machines." Memoire de l'Academie Royale Sciences 10(1781):161.

6. Irvine, C. H. "A New Slipmeter for Evaluating Walkway Slipperiness." Materials and Research Standards 7(12), December 1967.

7. James, D. I. "A Broader Lood at Pedestrian Friction." Rubber Chemistry and Technology Rubber Reviews 53(1980).

8. Perkins, P. J., and Wilson, M. P. "Slip Resistance Testing of Shoes - New Developments." SATRA, Kettering, 1982.

9. Rabinowicz, E. "Stick and Slip." Scientific American 194(5), May 1956.

10. Szymusiac, S. M., and Ryan, J. P. "Prevention of Slip and Fall Injuries." Professional Safety, June 1982, pp. 11-15.

APPENDIX A: OPERATING INSTRUCTIONS FOR EACH FRICTION TESTING DEVICE

This appendix gives operating instructions for each measurement device; in particular instructions for the Bigfoot are included because there were no other instructions in the literature or included with the device description from which it was built.

1. Bigfoot

The only statement of methods for using this device came form Harvey Cohen's description he provided for us: "Place assembled 'Bigfoot' onto surface to be rated and pull the gauge until the foot moves. Then take your reading from the gauge." Our suggested techniques, based on experience and the force platform experiments, are as follows:

1. Attach shoe material to bottom of holder with double-stick tape.
2. Sand bottom surface, and brush off residue.
3. Be sure floor surface has been cleared of loose residue.
4. Attach weight to shoe material holder.
5. Put the hook of the force gauge through the eye-clip on the front of the shoe material holder, making sure the gauge is positioned to read pounds instead of kilograms.
6. Lower the entire assembly onto the floor surface to be assessed.
7. Pull on the force gauge with a slow, steady force, making sure to keep the gauge as close to horizontal as possible; do not jerk the force gauge!

8. Read the static COF from the force gauge, and record it.
9. Reposition the device on the floor surface, and repeat the measurement.
10. Make ten measurements of COF for each shoe/floor condition.

When the floor surface, the shoe material, or both are wet, care must be taken to avoid adhesion phenomena: repeat the above steps through step 5, then lower the left edge of the shoe material holder to the surface, let the rest of the shoe material down rapidly, and pull before the sensor can rest on the floor surface for one second. We found these techniques decreased inter- and intra-operator differences.

2. Slipometer

The following set of instructions were included with the slipometer as supplied by Creativity, Inc :

Test Procedure

The following is a suggested method for conducting slip resistant tests of footwear materials and walkway surfaces.

1. Prepare the walkway surface to be used in the evaluation. Remove loose materials, dust surfaces.

2. Prepare the footwear test speciments. Mount in base of slipometer.

Clean surface of test specimens, lightly using sanding block. Use paint bursh to remove sandings.

3. Place slipometer on prepared walkway surface.

4. Place power unit in front of slipometer, approximately 12-15 inches. Align pulley with hook on the slipometer. Connect the string to hook on the slipometer.

5. Put red switch in center position. Zero the meter by moving rim on dial. Push red switch toward hookless end of meter. Hold string taut at center of pulley. Push down on power unit to prevent it from moving. Turn on power switch. Turn off power unit when slipometer moves.

7. Read dial for <u>slip index</u>.

8. Conduct 10 measurements at each surface to be tested and use average of the ten (10) measurements as the test value (procedure established by prior use).

Calibration of Slipometer

The following is the recommended procedure for calibration of the CREATIVITY HORIZONTAL SLIPOMETER.

1. Put red switch in center position. The red switch has three positions:

   A. Forward--not used.
   B. Rearward--when conducting tests.
   C. Center--used in calibration.

2. Hold SLIPOMETER in vertical position.

3. Zero the meter by moving rim on dial.

4. Use "T" hook provided to let slipometer hang freely.

5. Needle on dial should be within calibration (CAL) range on dial.

   Note: The needle should make one complete revolution of dial and point to the black band marked CAL on the dial. Failure to do so means the unit is out of adjustment and should be returned for repair.

3. NBS-Brungraber

These instructions were included with the device. Because of the complexity of the device, we felt unsure of our technique until visited by Dr. Robert Brungraber, who demonstrated his device. The calibration curve for the device is included, also.

Step by Step Operation of the NBS-Brungraber Slip-Resistance Tester

A. Perform the following procedure:

A.1 Carefully remove the tester from its case, inspecting for any loose or damaged parts.

A.2 Using a clean cloth or paper napkin, thoroughly wipe all parts of the main, horizontal travel bars that come in contact with the linear ball bushings in the carriage.

A.3 Select a sensor clip, having a suitable facing material, and clip it to the bottom of the sensor shoe, making certain that the vertical extension in the clip extends up through the hole in the base plate and lies behind the trigger. Also be certain that the clip is pushed back with respect to the shoe as far as it will go, so that the vertical extension on the clip is thoroughly engaged in the single notch at the front of the shoe.

A.4 Remove the indicator rod from the case and wipe it thoroughly with a clean cloth or paper napkin.

A.5. Insert the magnetic end of the indicator rod through the indicator tube at the front of the tester, pushing the rod back until the magnet engages the head of the adjustable carbon steel bolt attached to the carriage. While inserting the rod, be certain that the trigger-clutch assembly is thoroughly released by pushing the sensor shoe as far toward the rear of the tester as it will go. If the rod fails to slide in easily, it may be necessary to back off the adjustment screw in the upper end of the trigger. This is done by first releasing the knurled locknut on it.

A.6 Adjust the trigger mechanism by first putting the tester on a level surface, with the sensor shoe to the rear of its possible travel and with the carriage fully forward, with the initial stop, the short piece of flexible plastic tubing, removed. Then adjust the trigger so that the 0.05 in. (1.3 mm) thick spacer, supplied with the tester, can be easily placed between the trigger and the vertical extension on the front of the sensor clip. Set the trigger stop so that there is a 0.05 in. gap between the stop and the front of the trigger, with the trigger again at the front of its travel. At no time during these adjustments should the trigger be pushed hard enough to bend it. The 0.05 in. gap between the trigger and the stop permits some elastic bending of the trigger during operation of the tester, but the trigger should be free of bending stress while being adjusted.

A.7 With the carriage fully forward and the magnet on the indicator rod engaged with the bolt in the carriage, check the zero reading. If the zero line on the indicator rod does not lie opposite the notches in the indicator tube, bring them into alignment by releasing the thumb nut on the bolt in the carriage and adjusting it as needed. Before attempting to adjust the zero position of the indicator rod, first check the indicator tube to be sure it is tightly secured in the front of the tester and is so positioned that the indicator rod may be easily read from the top of the tester.

A.8 Check the free movement of the indicator rod by holding the sensor shoe in its rearward position and moving the carriage, by hand, throughout its travel. The indicator rod must travel freely, without breaking the magnetic attachment to the bolt in the carriage. If the rod does not move freely, check the rod for straightness. If the rod has been bent, it may be possible to carefully straighten it; if not, it must be replaced. During this operation, the sensor shoe can be held in its rearward position either by hand or by temporarily adjusting the trigger stop such that all movement of the trigger is prevented.

A.9 With the tester on a level surface and the sensor shoe again held in its rearward position, adjust the spring-control collar(s) so that the carriage will move freely throughout its entire travel, using the initial-position stop to initiate the travel. That is, the collar should be adjusted such that the carriage, while dragging the indicator rod, will just move to the end of its travel (the weight fully descended), without causing an excessive bump at the end of travel.

A.10 With the tester fully adjusted, the proper sensor in place, and the initial stop (the short piece of flexible plastic tubing) installed at the front of one of the main travel bars, conduct a test by picking up the tester by the handle, placing it on the area of the floor to be evaluated, and releasing the handle. Read the value of the resulting NBS-Brungraber number from the indicator rod at the index formed by the pair of notches in the indicator tube. Then convert the NBS-Brungraber number to an equivalent value of static coefficient of friction by means of the calibration chart or curve that are supplied with the tester. When picking up the tester, take care to see that the clutch is released permitting free movement of the indicator rod, before the indicator rod is forced forward to its initial position. This can most easily be done by inducing a slightly rearward force on the handle during the initial part of the picking-up operation. This assures that the sensor shoe is lifted free of the floor, thereby permitting it to return to its initial position, releasing the trigger and clutch, before the indicator rod is pushed by the carriage back to the initial position.

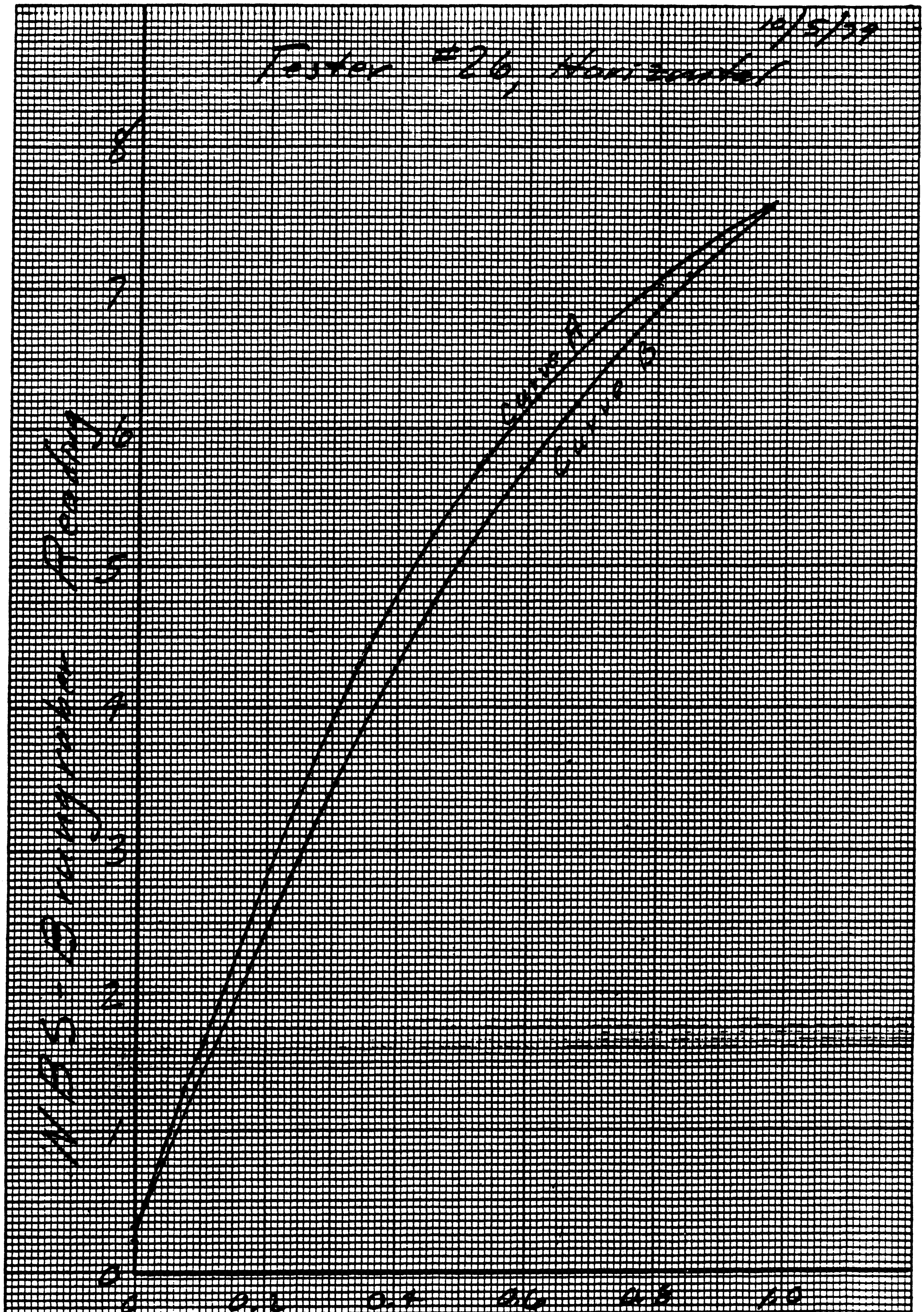
A.11 By repeating the procedure in 10, additional readings can be taken at the same or newly selected spots on the walking surface. When taking repeat tests at the same identical spot, hold the tester in place with one hand, and operate it with the other. In this case, exercise special care to be sure to apply a rearward bias to the handle when first lifting it to assure that the indicator rod is free to be returned to its starting position.

A.12 It should be noted that, with the initial-position stop in place, readings of less than 0.5, which corresponds to a static coefficient of friciton of about 0.03, cannot be taken. However, such values of coefficient of friction are quite low and would represent an extremely hazardous condition for most walking surfaces. In fact, the operator of the tester would have to exercise great care to prevent self injury. In the event the presence of water or other contaminant on the surface makes it so slippery that the tester registers a value equal to the initial setting of the tester, indicating that the indicator rod did not travel at all, a repeat test should be performed with the initial stop removed. In this case, the tester is not self-starting, and it will be necessary to impart a slight rearward push to the handle as soon as the sensor comes in contact with the floor. It is important that there be no delay between the contact of the sensor with the floor and the start of the carriage movement, since it is under those circumstances (the presence of water or other liquid contaminants) that a time delay will permit the squeezing-out of the contaminant, which may promote adhesion of the sensor to the floor and result in a unrealistically high indication of the slip resistance of the walking surface.

B. When evaluating extremely slippery surfaces such as bathtubs or shower bases in the presence of soapy water, certain modifications must be made to the previous instructions for the operation of the NBS-Brungraber Tester, which were for dry, level floors.

B.1 To promote free and complete drainage, most bathtub and shower base surfaces have a built-in slope, toward the drain, of about 1 1/2 to 2 degrees. By taking advantage of this slope and operating the NBS-Brungraber Tester "uphill," it can be adjusted so that it is self-starting without the use of the initial position stop. This permits the measurement of low values of coefficient of friction, less tha 0.03, while still retaining the desirable self-starting feature which reduces operator error. Thus, wherever possible, bathtub and shower surfaces should be tested "uphill" at a 1 to 2 degree slope and the tester should be adjusted and calibrated for this mode of operation.

B.2 Follow the instructions in A.1 through A.8 for use of the tester on slippery surfaces. For adjustment of the spring control collar(s), the adjustment should be carried out with the tester inclined "uphill" at the approximate angle it is to be used and with the initial-position stop removed. For the actual operation of the tester, the initial position stop must be removed and the test must be conducted in the "uphill" direction. If it is too difficult to incline the surface and it must be tested in the level position, satisfactory results can be obtained by carefully following the instructions in A.12. However, the tester must then be adjusted and calibrated for use on a level surface. When evaluating such surfaces as bathtubs or shower bases, particular care should be used to hold the tester in place with one hand while operating it with the other, since movement of the tester during the conduction of a test will result in a false reading.


10/5/39
Tester #26, Horizontal
NBS-Dynameter Reading
0
1
2
3
4
5
6
7
8
Curve A
Curve B
0
0.2
0.4
0.6
0.8
1.0
Static Coefficient of Friction, μ_s

APPENDIX B: DATA SHEETS FOR BOTH THE LABORATORY AND FIELD STUDIES

3= WET LEATHER

3= BRUNGRABER

TRIAL #	SHOE #	FLOOR #	DEVICE	CONDITI	OPERAT	1	2	3	4	5	6	7	8	9	10
				DRY											
				WAX											
				WET											
				SOAP											

B.1. LABORATORY DATA SHEET

TASK	TIME	DEVICE #	SHOE #	OP #	READINGS / COMMENTS
ARRIVE AT SITE	0				FLOOR AND LOCATION DESCRIPTION:
SET-UP AND CALIBRATE DEVICE					
TAKE READINGS					1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10
DISASSEMBLE DEVICE AND REPACKAGE					SUBJECTIVE RATINGS IN THIS SETTING (1-5; 1= NOT VERY, 5= EXTREMELY) EASE OF USE ( ) REPEATABILITY ( ) UTILITY IN THIS SETTING ( )
ARRIVE AT SITE					FLOOR AND LOCATION DESCRIPTION:
SET-UP AND CALIBRATE DEVICE					
TAKE READINGS					1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10
DISASSEMBLE DEVICE AND REPACKAGE					EASE OF USE ( ) REPEATABILITY ( ) UTILITY IN THIS SETTING ( )
ARRIVE AT SITE					FLOOR AND LOCATION DESCRIPTION:
SET-UP AND CALIBRATE DEVICE					
TAKE READINGS					1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10
DISASSEMBLE DEVICE AND REPACKAGE					EASE OF USE ( ) REPEATABILITY ( ) UTILITY IN THIS SETTING ( )

B.2. FIELD DATA SHEET

SHOE:
1= DRY LEATHER
2= RUBBER COMBO
3= WET LEATHER

DEVICE:
1= BIGFOOT
2= SLIPOMETER
3= BRUNGRABER

FLOOR DESCRIPTIONS:
1: SURFACE TYPE
2: MAINTENANCE
3: TRAFFIC

272-101

EPORT DOCUMENTATION PAGE	**1. REPORT NO.** IOE/CE - 83/01	**2.**	**3. Recipient's Accession No.**

Title and Subtitle
Bibliography of Coefficient of Friction Literature
elating To Slip Type Accidents

5. Report Date
February 1983

6.

Author(s)
ames M. Miller P.E., Ph.D.

8. Performing Organization Rept. No.

Performing Organization Name and Address
epartment of Industrial and Operations Engineering
he University of Michigan
nn Arbor, Michigan 48109

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C) B9F16956
(G)

. Sponsoring Organization Name and Address
ccupational Safety and Health Administration
.S. Department of Labor
00 Constitution Avenue
ashington, D.C. 20210

13. Type of Report & Period Covered

14.

. Supplementary Notes

Abstract (Limit: 200 words)

In the bibliography contained herein, this author has compiled a list f references which address various aspects of coefficient of friction OF) as it relates to slip type accidents. Included are topics such as riction measurement machines, floor slipperiness, shoe sole COF values, nd required COF for walking and a few work type tasks. The references ere collected as cited from among over thirty-five notable publications hich have appeared over the past fifty years. The result is over three undred references originating from books, periodical articles, technical eports, proceedings, and standards. It is believed that this is urrently the most complete set of collected references in the field. ecause of his continuing safety research activities in this area, the uthor intends to update regularly the computerized collection which this epresents. Others interested in seeking further information about the eferences or who wish to make suggestions or contributions are invited o do so.

Document Analysis a. Descriptors
riction, Slips, Falls, Slippery, Slip Resistant, Shoes, Floors,
rk Surfaces, Measurement of Friction, Coefficient of Friction

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

Availability Statement Unlimited	**19. Security Class (This Report)**	**21. No. of Pages**
	20. Security Class (This Page)	**22. Price**

ANSI–Z39.18) **See Instructions on Reverse** **OPTIONAL FORM 272 (4–77)**
(Formerly NTIS–35)
Department of Commerce

A BIBLIOGRAPHY
OF
COEFFICIENT OF FRICTION LITERATURE RELATING TO SLIP TYPE ACCIDENTS

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FEBRUARY 1983

This paper and its background research were supported in part by the Directorate of Safety Standards, Occupational Safety and Health Administration, U.S. Department of Labor

FOREWARD

Several papers from the past eight years have been notable in their treatment of coefficient of friction research in relation to slip/fall type accidents. Key among these were Reed(1975), Pfaust and Miller(1976), Brungraber(1976), Adler and Pierman(1979), and James(1980). Most of these papers have good bibliographies associated with them. However, the subsets of publications within their bibliogaphies varies considerably.

In the bibliography contained herein, this author has compiled a collected list of references cited from the above mentioned and some thirty other relevant publications. The result is over three hundred references originating from books, periodical articles, technical reports, proceedings, and standards.

Readers are advised that numerous reference citations are incomplete by today's standards. This is usually because the original citations from the source documents were themselves incomplete and not traceable by this author. The sources from which the citations originated are listed under the column entitled "Citation Index Number", the key to which appears at the end of this paper. Those references already in this author's personal library are given the designation "0" thereunder.

It is believed that this is currently the most complete set of collected references in the field. Because of his continuing safety research activities in this area, the author intends to update regularly the computerized collection which this represents. Others interested in seeking further information about the references or who wish to make suggestions or contributions are invited to do so.

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BOOKS

	Citation Index Number
Basmajian, J. V. *Muscles Alive.* 3rd ed. Baltimore: Williams and Wilkins, 1974.	8
Bowden, F. P., and Tabor, D. *The Friction and Lubrication of Solids.* Oxford: Clarendon Press, 1958, p. 372.	
Damon, A.; Stoudt, H. W.; and McFarland, R. A. *The Human Body in Equipment Design.* Harvard University Press, 1966.	
Contini, R.; Gage, H.; Dulles, R. *Human Gait in Characteristics in Biomechanics and Related Bioengineering Topics.* Edited by R. M. Kenedi. Oxford: Pergamon Press, 1965.	26
Edwards, A. L. *Experimental Design in Psychological Research.* New York: Holt, Rinehart, and Winston, February 1960.	16
Leveau, B. *Williams and Lessner: Biomechanics of Human Motion.* Philadelphia: W. B. Saunders, 1977.	8
Ling, F. F.; Klaus, E. E.; and Fein, R. S. *Boundary Lubrication, An Appraisal of World Literature.* New York: ASME Research Committee on Lubrication, 1969, p. 576.	
Manley, R. G. *Waveform Analysis.* London: Chapman and Hall, 1945.	26
McCormick, E. J. *Human Factors in Engineering and Design.* 4th ed. New York: McGraw-Hill, 1976.	8
Rabinowicz, E. *Friction and Wear of Materials.* New York: John Wiley and Sons, Inc., 1965, p. 244.	24
Ralston, A., and Wief, H., eds. *Mathematical Methods for Digital Computers.* New York: John Wiley and Sons, Inc., 1960.	26

PERIODICAL ARTICLES

Anonymous Periodical Articles

	Citation Index Number
American Society for Testing and Materials. *ASTM Bulletin 196*. Philadelphia: ASTM, February 1954.	16
American Society for Testing and Materials. "ASTM D1894-63 Standard Method of Testing for Coefficient of Friction of Plastic Fibers."	24
American Telegraph and Telephone Company. "Bell Systems Practices, Measurement of Slip-Resistance of Resilient Floors, Principles and Evaluation." *American Telegraph and Telephone Company Standard H51:119*, August 1955.	9
"Answers to the Problems of Unsafe Surfaces Include Plates, Mats, Coatings, and Housekeeping," *National Safety News*, August 1980.	0
"BS 3424 Methods of Testing for Coated Fabrics, Method 12, Determination of Surface Drag."	24
"Complex Analysis Produces 'Signature' of Human Step." *Product Engineering*, July 1, 1968.	19
Chemical Specialties Manufacturers Association. "CSMA Procedure for Products Classified as to Slip Resistance." *CSMA Bulletin #308-70*, December 1982.	19
"Exploring Traction of Floor Surfaces in 'Materials Research and Standards'." *Materials Research and Standards Bulletin* 35(4), November 1972, pp. 33-34.	14
"How an Antislip Sole was Born," *National Safety News*, August 1980.	0
National Board of Occupational Safety and Health. *Occupational Injuries 1979, 1st (2nd, 3rd) Quarter*. Official Statistics of Sweden, 1980.	
National Central Bureau of Statistics. *Causes of Death 1975*. Official Statistics of Sweden, 1977.	23

	Citation Index Number
National Social Insurance Board. *Occupational Injuries 1975.* Official Statistics of Sweden, *1979.*	
"Soles and Heels, Rubber, Traction Tread, Shoe." *Military Specification MIL-S-22777B*, June 1967.	7
"Solving the Problem of Unsafe Surfaces Begins with Selecting Correct Flooring," *National Safety News*, August 1980.	0

Authored Periodical Articles

	Citation Index Number
Abrahamson, E. "Zur Kenntnis Der Mechanik Des Mittelfusses." Arch. F. Hypsical 51(1927), Skandinavia, pp. 175-234.	19
Amar, J. "Trottoir Dynamographique." Acad. D. Sc. 163(1916):130-132.	19
Amontons, M. "De la Resistance Causee dans les Machines." Histoire de l'Academie Royale de Sciences, 1699, p. 206.	10
Andriacchi, T. P.; Ogle, J. A.; and Galante, J. O. "Walking Speed as a Basis for Normal and Abnormal Gait Measurements." J. Biomech. 10:261-8.	23,27
Barrett, G. F. C. "Observations on the Coefficient of Friction of Shoe Soling Materials." Rubber Journal 131(22), 1956, pp. 685-688.	20,19
Bartenev, G. M., and Elkin, A. I. "Frictional Properties of Polymers in the Non-Steady State Stages of Sliding at High and Low Temperatures." Polymer Science USSR (Vysokomolekulyarnye Soedineniya 7) 7(6), 1965, pp. 1095-1101.	20
Bartenev, G. M., and Lavrentev, V. V. "The Nature of Static Friction in Elastomers." Rubber Chemistry and Technology (Vysokomolekulyarnye Sodineniya 2) 34(1961):461-465.	20
Bartenev, G. M. "Theory of Dry Friction of Rubber." Doklady Akademiya Nank SSSR 96(6), 1954, pp. 1161-1164.	20
Basler, A. "Kinematographische Aufnahem Mit Gleichzeitiger Registrierung Von Kraeften." Arbeitsphyl 8(1935):585-590.	19
Beely, F. "Zur Mechanik Des Stehens." Arch. F. Klin. 27(1882):457-471.	19
Bernstein, N. A. "Biodynamics of Locomotion," . . . 1(1935), Moscow.	19

	Citation Index Number
Bernstein, N. "Untersuchungen der Biodynamik des Ganges und des Laufes." Moscom, 1927.	28
Betts, R. P., and Duckworth, T. "A device for measuring plantar pressures under the sole of the foot." Eng. Med., Vol. 7, 1978.	28
Bianca, D. "Sliding Friction and Abrasion of Elastomers." Rubber World 156(6), 1967, pp. 65-67.	20
Bocelli, G. A. . . . De Motu Antimatum, 1979.	
Bowden, F. P., and Tabor, D. "The Friction and Lubrication of Solids Parts I and II." Oxford at the Claredon Press, 1964.	19
Bowden, F. P., and Leben, L. "The Nature of Sliding and the Analysis of Friction." Proceedings of the Royal Society of London, London, 169(1938-1939):371-391.	19
Braun, R., and Roemer, D. "Influence of Waxes on Static and Dynamic Friction." Soap/Cosmetics/Chemical Specialties Federal Specification P-W-155, West Germany, December 1974, pp. 60-72.	14,19
Bresler, B., and Frankel, J. P. "The Forces and Moments in the Leg During Level Walking." American Society of Mechanical Engineers 72(1), January 1950.	19
Bung, C. "Slip up safety testing." Royal Institute of Technology, Stockholm, 1978.	23
Brough, R.; Malkin, F.; and Harrison, R. . . . Journal of Physics D: Applied Physics 12(4), 1979, pp. 517-528.	20
Carlet, M. G. "Essai Experimental Sur la Locomotion Humain, Etude de la Marche." Ann. D. Scien. Mat. Zool. 16(1872):1-92.	19,22
Carlsoo, Sven. "A Method for Studying Walking on Different Surfaces." Ergonomics 5(1962):271-274.	14
Charnley, J., and Pusso, R. "The recording and analysis of gait in relation to the surgery of the hip joint." Clin. Orthop. related Res. 58:153-164, 1968.	26
Conant, F. S., and Liska, J. W. "Friction Studies of Rubberlike Materials." Rubber Chem. Technology 33(1781):161	19

	Citation Index Number
Corless, D. "The Aging Skeleton." The Practitioner 225, 1981, pp. 1775-1785	21
Coulomb, C. A. "Theory of Simple Machines." Memoire de l'Academie Royale Sciences 10(1781):161.	10,19
Cramp, A. P., and Masters, L. W. "Preliminary Study of the Slipperiness of Flooring." National Bureau of Standards NBSIR 74-613, November 1974.	10,0,19
Cunningham, D. M. "Components of Floor Reactions During Walking." Prosthetic Devices Research Project, Institute of Engineering Research, University of California, Berkley, Advisory Committee on Artificial Limbs, National Research Council, Series II, Issue 14, November 1950.	19
Cunningham, D. M., and Borwn, W. O. "Two Devices for Measuring the Forces Acting on the Human Body During Walking." University of California, Berkley: Proceedings of Society for Experimental Stress Analysis 9(2), 1952.	19
Day, S. S., and Hodges, M. B. "Factors Affecting Skid Resistance of Hard Floor Surfaces." Hospitals, J.A.H.A. 41, April 16, 1967.	19
Day, S. S., and Shamburger, E. "Factors Controlling Skid Resistance of Hard Floor Surfaces," Hospitals, J.A.H.A. 39, April 16, 1965.	18,19
Day, S. S.; Tuten, F.; Trogdon, J.; and Bowen, H. "Measurement of the Skid Resistance of Resilient Smooth Floor Surfaces." Journal of Home Economics 56(10), December 1974.	19
de Coste, J. B. "Friction of vinyl chloride plastics." SPE J. 25(10), Oct. 1969, p. 67.	24
Derieux, J. B. "The Coefficient of Friction of Rubber." Journal of the Elisha Mitchell Scientific Society 50(1934):53-55.	20
Diaganich, L. F.; Andriacchi, T. P.; Strongwater, A. M.; and Galanti, J. O. "Electronic Measurement of Instantaneous foot-floor contact patterns during gait." J. Biomechanics, Vol. 13, 1979.	0
Ekkebus, C. E., and Killey, W. "Measurement of Safe Walkway Surfaces." Soap/Cosmetics/Chemical Specialties, February 1973.	14,19,22

	Citation Index Number
Elftman, H., and Manter, J. . . . Science 88(1938):152.	13,0,19
Elftman, H. . . . Anatomical Record 59(1934):481.	13,19,24
Elftman, H. "Forces and energy changes in the leg during walking." American Journal of Physiology, Vol. 125, 1939.	0
Elftman, H. . . . Arbeitsphysiologic 10(1939):485.	13,19
Esmay, M. L., and Segerlind, L. J. "Analysis of Frictional Characteristics of Stairway Tread Covering Materials." Transactions of the Am. Soc. of Agricultural Engin. 7(2), 1964, pp. 180-183, 189.	5,19
Fisher, O. "Der Gang Des Menchen, II Theil: Die Bewegung Des Gasammtschwerpunktes And Die Ausseren Krate, Abhandlugen Der Mathematisch-Physischeclasse Der Koniglish Sachsischen." Gesellschaft Wissenschaften, Leipzig, 25(1895):31-130.	18,22,28
Gage, H. "Accelerographic analysis of human gait." A.S.M.E. Biomechanics Monograph. 1967, p. 137.	26
Gaven, F. M., and Vanaman, J. B. "Significant Variables Affecting Results Obtained with the James Friction Machine." Materials Research and Standards, November 1968.	0
Giles, C. G.; Sabey, B. E.; and Cardew, K. H. F. "Development and Performance of the Portable Skid Tester." Rubber Chemistry Technology 38(1965):840.	10,23
Grosch, K. A. "The Relation Between the Friction and Visco-Elastic Properties of Rubber." Proc. Roy. Soc. A. 274(1356), June 1963.	23
Grieve, D. W., and Gear, R. J. "The Relationship Between Length of Stride, Step Frequency, Time of Swing and Spped of Walking for Children and Adults." Ergonomics 5(1966).	23
Grundy, M.; Tosh, P. A.; McLeish, R. D.; and Smidt, L. "An investigation of the centers of pressure under the foot while walking." J. Bone Jnt. Surg. 57-B(1975):98-103.	24
Gustafsson, C., and Lanshammai, H. " ENOCH - are Integrated System for Measurement and Analysis of Human Gait." UPTEC 77 23R, Institute of Technology, Uppsala University, Sweden, 1977.	23

	Citation Index Number
Harper, F. C.; Warlow, W. J.; and Clarke, B. L. "The Forces Applied to the Floor by the Foot in Walking." Her Majesty's Stationary Office, National Building Studies Research Paper 32, London, 1961.	9,0,22, 27
Hopkins, S. K. "Elusive Factors in Falls: The Shoe Sole." National Safety News 9(5), 1966, pp. 31-39.	9
Holden, T. S., and Muncey, R. W. "Pressures on the human foot during walking." Aust. J. Appl. Sci. 4:405-17.	27
Hunter, R. B. "A Method of Measuring Frictional Coefficients of Walkway Materials." Journal of Research, National Bureau of Standards 5(1930):329.	9,0,22, 19
Hurry, J. A., and Prock, J. D. "Coefficients of Friction of Rubber Samples." India Rubber World 128(5), 1953, pp. 619-622.	20
Hutton, W. C., and Drabble, G. E. "An apparatus to give the distribution of vertical load under the foot. Rheum. Phys. Med. 11:313-17.	27
Irvine, C. H. "Evaluation of Some Factors Affecting Measurements of Slip Resistance of Shoe Sole Materials on Floor Surfaces." J. of Testing and Evaluation 4(2), March 1976, pp. 133-138.	0
Irvine, C. H. "Shoe Sole Slipperiness on Structural Steel." Materials Research and Materials 10(4), April 1970, p. 21.	0
Irvine, C. H. "A New Slipmeter for Evaluating Walkway Slipperiness." Materials Research and Standards 7(12), December 1967, pp. 535-542.	0
Jacobs, N. A.; Skorecki, J.; and Charnly, J. "Analysis of the Vertical Component of Force in Normal and Pathological Gait." J. of Biomechanics 5(1972).	99
James, D. I. "A Broader Look at Pedestrian Friction." Rubber Chemistry and Technology 153(3), July/August 1980, pp. 512-541.	14,20
James, D. I., and Newell, W. G. "A New Concept in Friction Testing." Polymer Testing, Rapra Members' Report 20 1(1), 1978, pp. 9-25.	20
James, D. I. "Measurement of Friction Between Rubber Like Polymers and Steel." J. of Sci. Inst. 38(7), July 1961.	23

	Citation Index Number
James, D. I. "Variation in the Friction of Rubbers and Plastics." RAPRA Report #1, July 1973.	23
James, S. V. "What is a Safe Floor Finish?" Soap and Sanitary Chemicals 20, October 1944, pp. 111-115.	10,20
Kellett, P. H. "Modern Solings in Wear." Shoe and Allied Trades Association, IP 16, Northants, UK, October 1969, p. 21.	
Laubach, L. L., and McConville, J. T. "The Relationship of Strength to Body Size and Typology." Medicine and Science in Sports 1(4), 1969, pp. 89-97.	7
Lavrentev, V. V. "Static Friction and the Law of Rubber Friction." Rubber Chemistry and Technology 36(2), April/June 1963, pp. 365-376.	
Leroux, M. "Etude de l'Adherence of Resilient Floors, Principles and Evaluation." State Road Laboratory, Section H51.119, The Hague, 00(310), November 1957, pp. 43-45.	13
Malkin, F., and Harrison, R. "A Small Mobile Apparatus for Measuring the Coefficient of Friction of Floors." Journal of Physics, D: Applied Physics 13(1980):177-179	20
Manning, D. P., and Shannon, H. S. "Slipping Accidents Causing Low Back Pain in Gearbox Factory." Spine 6(1), 1981, pp. 70-72.	0,21
Norman, R. H. "Some Aspects of the Friction of Elastomeric Plastics." Rheological Abstracts 3(3), 1960.	20
Ohlsson, E.; Formgren, C.; and Nordstrom, O. "Road friction (in Swedish)." National Road and Traffic Research Institute, Sweden, 1972.	23
Pfauth, M. J., and Miller, J. M. "Work Surface Friction Coefficients: A Survey of Relevant Factors and Measurement Methodology." Journal of Safety Research 8(2), June 1976.	0,18
Rabinowitz, E. "The intrinsic variables affecting the stick-slip process." Proc. Phys. Soc. 71(460), Pt. 4, April 1958, p. 668.	24
Ratner, S. B., and Larentev, V. V. "Evidence for the Static Friction of Unlubricated Rubber." Doklady Akademii Nauk, SSSR 108(3), 1956.	20

	Citation Index Number
Roberts, A. D., and Thomas, A. G. "Static Friction of Unlubricated Rubber." NR Technology 7(2), 1976, pp. 38-42.	20
Roth, F. L.; Driscoll, R. L.; and Holt, W. L. "Frictional Properties of Rubber." Journal of Research, National Bureau of Standards 28(4), 1942, pp. 439-462.	20
Saunders, J.; Inman, V.; and Eberhart, H. "The major determinants in normal and pathological gait." J. Bone Jt. Surg. 35A(1953):543-58.	26
Schwartz, R. P.; Heath, A. L.; Morgan, D. L.; and Towns, R. C. "A quantitative analysis of recorded variables in the walking pattern of "normal" adults." J. Bone Jnt. Surg. 46-A(1964):324-34.	27
Scranton, P. E., Jr., and McMaster, J. H. "Momentary distribution of forces under the foot." J. Biomech. 9(1976):45-8.	27
Seireg, A., and Arvikar, R. J. "The Prediction of Muscular Load Sharing and Joint Forces in the Lower Extremities During Walking." Journal of Biomechanics 8(1975):89-102.	8
Sigler, P. A.; Geib, M. N.; and Boone, T. H. "Measurement of the Slipperiness of Walkway Surfaces," J. of Research, NBS 40(1948):339-346.	0,7,9 19,22
Sigler, P. A. "Relative Slipperiness of Floor and Deck Surfaces." Building Materials and Structures Report, National Bureau of Standards, BMS 100, July 1943.	9,0, 19,22
Skorecki, J. "The design and construction of a new apparatus for jmeasuring the vertical forces exerted in walking: a gait machine." J. Strain Analysis I(1966):429-38.	26
Stokes, A. F.; Stott, J. R. R.; and Hutton, W. C. "Force distributions under the foot-a dynamic measuring system." Biomed. Engng., April, 1974, pp. 140-3.	27
Stott, J. R. R.; Hutton, W. C.; and Stokes, I. A. F. "Forces under the foot." J. Bone Jnt. Surg. 55-B(1973):335-44.	27
Strandberg, L. and Lanshammar, H. "The Dynamics of Slipping Accidents." J. of Occupational Accidents, Amsterdam, 3(1981):153-162.	0

	Citation Index Number
Thornton-Trump, Daher, R. "The Prediction of Reaction Forces from Gait Data." Journal of Biomechanics 8(1975):173-178.	8
Tisserand, M. "Criteres d'adherence des semelles de securite." Institut National de Recherche et de Securite, Nancy, France, 1969.	23
Waller, J. A. "Falls among the elderly--human and environmental factors. Accid. Anal. Prev., 10(1978):21-33.	23
Warwick, D.; Novak, G.; and Schultz, A. "Maximum Voluntary Strengths of Male Adults in Some Lifting, Pushing, and Pulling Activities." Ergonomics 23(1), 1980.	19
Williams, W. D.; Smith, J. A.; and Draugelis, F. J. "Topaka, A New Device and Method for Measuring Slip-Resistance of Polished Floors." Soap/Cosmetics/Chemical Specialties, July 1972.	10
Wilson, A., and Mahoney, P. "Measuring Frictional Properties of Soles and Heels." Rubber World, March 1972, pp. 36-37.	0

TECHNICAL REPORTS, PROCEEDINGS, AND STANDARDS

Anonymous Authors

	Citation Index Number
"An investigation of skid resistance in Missouri, Study 69-3." Missouri State Highway Dept., Jefferson City, MO, August 1973.	0
"Bell System Practices, Measurement of Slip-Resistance of Resilient Floors, Principles and Evaluation," American Telephone and Telegraph Co. Standard, Section H51.119, August 1955.	13
"Causes and Measurement of Walkway Slipperiness, Federal Construction Council Technical Report #43," National Academy of Sciences, National Research Council Pub. 899, Washington, D. C., 1961.	10,0, 19,22
"Coefficient of Friction (Slip) Measurements," Instrn Corp., G-63-10 Fixture, Canton.	19
"Comparative Determination of Slip Resistance of Floor Polishes." CSMA Tentative Method. CSMA Bulletin 245-70, July 1970.	19
"CSMA Bulletin 245-70, Wakes, Polishers and Floor Finishes Division." July 1970.	19
"CSMA Procedure for Products Classified as to Slip Resistance," Chemical Specialties Manufacturers Association, CSMA Bulletin 308-70, December 8, 1970.	12,19
"Deaths from Falls in England, Wales and Scotland," Mortality Statistics, Cause Office of Population Censuses and Surveys, 1979.	21
"Electronic Stepmeter Reveals Mechanics of Walking," National Bureau of Standards, NBS Tech. Bulletin 35(4), 1951.	14,19,22
"Exploring Traction of Floor Surfaces," Material Research and Standards Bulletin, November 1972, pp. 33-34.	9

Anonymous Reports

	Citation Index Number
"Falls on Floors," National Safety Council. Data Sheet I-495-81, 1981	0
"Falls," National Safety Council. Data Sheet No. 5, Chicago.	0
"Final Report," Final Report, National Commission on Product Safety, Washington, D. C., June 1970, pp. 39-42.	
"Floor Research Projects." Swedish Council for Building Research, Stockholm, May 1977.	0
"Fundamental Studies of Human Locomotion and Other Information Relating to the Design of Artificial Limbs," University of California, Report to U.S. National Research Council, 1947.	10
"How an Antislip Sole was Born," National Safety News, November 1966, pp. 38-39.	0
"Instructions for Using the Portable Skid-Resitance Tester, Road Research," Dept. of Scientific and Industrial Research, Her Majesty's Stationary Office Road Note No. 7, London, 1960.	10,13
"Introduction to Work Study," International Labor Office, Geneva, 1962, p. 67.	16
"Measurement of the Slipperiness of Walkway Surfaces," National Bureau of Standards, Research Paper 1879, Washington, D. C., 7(2) May 1948.	16,0
"MIL-D-3134F Military Specification for Deck Covering Materials,"	18
"Model 80 Floor Friction Tester," Technical Products Co., Promotional Literature, Caldwell, NJ.	10
"Outline of the Proposed Investigation for Determining the Slip Resistance of Floor Treatment Materials," Underwriters Laboratory, Subject 410, Northbrook, January 1974, p. 15.	0,19
"Proposed Trade Practice Rules for the Floor Wax and Floor Polish Industry," Federal Trade Commission, March 17, 1953.	12
"Safety Code for Floor and Wall Openings, Railings, and Toe Boards," American National Standards Institute, Standard A12.1, New York.	17

	Citation Index Number
"Standard Method for Measuring Surface Frictional Properties Using British Portable Tester," Part 15 1974 Annual Book of ASTM STDS, American Society for Testing and Materials, E303-74, Philadelphia, April 1974, pp. 810-815.	0,19
"Standard Method of Test for Coefficients of Friction of Plastic Film," Part 35 1974 Annual Book of ASTM STDS, American Society for Testing and Materials, D1894-73, Philadelphia, April 1974, pp. 563-568.	0,19
"Standard Method of Test for Measuring Surface Frictional Properties Using the British Portable Tester," American Society for Testing and Materials, ASTM E303-69, Philadelphia.	0,22,19
"American Society for Testing and Materials," ASTM D 2047, 1975.	10,0 19,22
"Standard Method of Test for Abraison Resistance of Soles and Heels." ASTM D-1630, Philadelphia, PA	19
"Standard Methods for Applications of Emulsion Floor Polishes to Substrates for Testing Purposes," American Society for Testing Materials, ASTM D 146, 1971.	10
"STD Method of Test for Static Coefficients of Friction of Polish-Coated Floor Surfaces Measured by James Machine," Part 30 1974 Annual Book of ASTM STDS, American Society Footing and Materials, D2047-72, Philadelphia, November 14, 1974, pp. 302-305.	0
Underwriters Labortory Reexamination Service, "Floor Coating and Finishing Materials."	0,19
"Walkway Surfaces: Measurement of Slip Resistance." STP 649, ASTM, 1978.	19
"Wax, Floor, Water-Emulsion, Slip-Resistant," Federal Specification P-W-155.	13
"Waxes, Polishes, and Floor Finishes Division," CSMA, CSMA Bul. 245-70, July 22, 1970.	19

Authored

	Citation Index Number
Adler, S. C., and Pierman, B. C. "A History of Walkway Slip-Resistance Research at the National Bureau of Standards," National Bureau of Standards, NBS Special Publication 565, Washington D. C., December 1979.	0
Allcott, G. A. "Slips, Trips, and Falls - Working Surfaces and Industrial Stairs," U.S. Dept. of H.E.W., Morgantown, WV, April 1979.	0
Ayoub, M. M., and McDaniel, J. W. "Effects of Operator Stance on Pushing and Pulling Tasks," AIIE Transactions, September 1974.	0
Bartenev, G. M., and Laventev, V. V. "Friction and Wear of Polymers," Elsevier Scientific Publishing Co., Lieng-Huang Lee and Ludema, K. C. 1972, Oxford, 1971.	20
Bartenev, G. M.; Lavrentjev, V. V.; and Konstantinova, N. A. "The Actual Contact Area and Friction Properties of Elastomers Under Frictional Contact with Solid Surfaces," Rubber Chemistry and Technology 45(1972):1094-1103.	
Blackmore, B., and Clark, D. "The Coefficient of Friction between Polyvinyl Chloride Conveyor Belting and Steel Driving Drums," National Coal Board, Central Research Establishment, Report No. 2009, 1954.	20
Boone, T. H., and Auld, C. W. "Standard Measurements of Slipperiness on Walking and Roadway Surfaces," Progress Report 1, National Bureau of Standards, NBS Report #7510, May 21, 1962.	19,22
Bowden, F. P., and Tabor, D. "The Friction and Lubrication of Solids, Part Two," Clarendon Press, Oxford, 1964.	19
Braun, R., and Brungraber, R. J. "A Comparison of Two Slip Resistance Testers Walkway Surfaces: Measurement of Slip Resistance," Presented at ASTM Symposium in Denver, Philadelphia, June 30, 1977.	0

	Citation Index Number
Bresler, B., and Berry, F. R. "Energy and Power in the Leg During Normal Level Walking," Institute of Engineering Research, University of California, Prosthetic Devices Research Project, Berkley, May 1951.	19
Brungraber, R. J. "A New Portable Tester for the Evaluation of the Slip Resistance of Walkway Surfaces, National Bureau of Standards, Technical Note 953, August 1977.	0
Brungraber, R. J. "An Overview of Floor Resistance Research with Annotated Bibliography," National Bureau of Standards, NBS Technical Note 895, Washington, D. C., January 1976.	0
Brungraber, R. J., and Adler, S. C. "Technical Support for a Slip-Resistance Standard Walkway Surface: Measurement of Slip-Resistance," Presented at ASTM Symposium in Denver, Philadelphia, June 30, 1977.	19
Bunten, J. "Friction Measurements on Soles and Heels, with Particular Reference to Woman's Top Piece Materials," Shoe and Allied Trades Research Association, SATRA Technical Memorandum 1344, Kettering, 1967.	19
Carlsoo, S. A. "A Method for Studying Walking on Different Surfaces," Ergonomics 5(1962):271-274.	9,0, 19
Carlsoo, Sven. "How Man Moves, Kinesiology Methods and Studies," Heinmann, London, 1972.	10,19
Carson, D. H.; Archea, J.; Marguis, S. T.; and Carson, F. C. "Safety on Stairs," NBS Science Series, National Bureau of Standards 10, December 1978.	14
Chaffin, D. B.; Olson, M.; and Garg, Arun. "Volitional Postures During Maximal Push/Pull Exertions in the Sagittal Plane," Human Factors Society, Inc., 25th Annual Meeting of Human Factor, 1981.	0
Conant, F. S., and Liska, J. W. "Friction Studies on Rubber Like Materials," Rubber Chemistry and Technology 33(1960):1218.	
Connor, John D., and Steinle, V. "Waxed Floors are Safe," Chemical Specialties Manufacturing Association, CSMA Mid-Year Meeting, Chicago, May 1961.	18

	Citation Index Number
Cramp, A. P., and Masters, L. W. "Preliminary Study of the Slipperiness of Flooring," National Bureau of Standards, NBSIR 74-613 33(1781):161.	19
Crumlish, R. J. "Slips and Falls in Industry," National Safety News, May 1981.	0
CSMA. "CSMA Procedure for Products Calssified as to Slip Resistance," Chemical Specialties Manufacturers Association, CSMA Bul. 308-70, December 8, 1928.	0,19
Day, S. S.; Bowden, H. D.; and Hader, R. J. "Skid Resistance of Floor Surfaces and Finishes," The University of North Carolina, Tech. Bulletin No. 200, December 1980.	18,19
Doering, R. D. "Defining a Safe Walking Surface," National Safety News, August 1974, pp. 53-58.	0,19
Edosomwan, J. A., and Khalil, T. M. "Accident Prevention in Slips and Falls - Plates, Mats, Coatings, and Housekeeping," Professional Safety, June 1981.	14
Edwin; Smith; Papyrus; and Breasted, J. H. "Case 33," The University of Chicago Press, Chicago, 1930, p. 338.	21
Egtvedt, R. "ASTM Proceedings of F13.10 Traction Subcommittee Meeting," American Society of Testing and Materials, Philadelphia, March 24, 1975.	
Ekkebus, D. F., and Killey, W. "Measurement of Safe Walkway Surfaces," Soap/Cosmetics/Chemical Specialities 49, February 1973, pp. 40-45.	0
Ernst, H., and Merchant, M. E. "Surface Friction of Clean Metals." Proceedings on Friction and Surface Finish, MIT, June 1940.	19
Fitch, J. M.; Templer, J.; and Corcoran, P. "The Dimensions of Stairs," Scientific American 231(1974):82-92.	9
Fox, W. F. "Body Weight and Coefficient of Friction as Determiners of Pushing Capability," Lockheed-Georgia Company, Human Engin. Studies Memo. No. 17, Marietta, GA, August 10, 1967.	0

	Citation Index Number
Frederick, W. S. "Description of a New Portable Slip Testing Machine," 44th Mid-Year Meetings Proceedings CSMA, Chemical Specialities Manufacturers Association, I, May 1958, p. 3.	19
Gavan, F. M., and Vanaman, J. B. "Significant Variables Affecting Results Obtained with the James Friction Machine," Materials Research and Standards 8, November 1968, pp. 16-18.	0
Giles, C. G.; Sabey, B. E.; and Cardew, K. H. F. "Development and Performance of the Potable Skid-Resistance Tester," U.K. Dept. of Scientific & Industrial Research, Tech. Paper 66, 1964	20
Gooch, H. D. "A Comparison of Four Methods of Measuring Slip Resistance of Floor Polishes," Chemical Times and Trends, July 1981, pp. 47-51.	20
Greater London Council. "Slip Resistance of Floors, Stairs and Pavings," Architects' Dept. Bulletin 43, 1971.	20
Grosch, K. A. "Relation between the Friction and Viscoelastic Properties of Rubber," Proceedings of the Royal Society 274(1963: 21-39.	20
Grosch, K. A. "The Relation between the Friction and Viscoelastic Properties of Rubber," Rubber Chemistry and Technology 37(1964):386-403.	24
Gurney, W. W. "Is the Floor Too Slippery?" National Safety News 38, August 22, 1940.	10,0
Hopkins, S. K. "Elusive Factors in Falls: The Shoe Sole," National Safety News 94(5), 1966, pp. 34-39.	0,14
Hunter, R. B. "A Method of Measuring Frictional Coefficients of Friction of Polish Coated Floor Surfaces," American Society for Testing & Materials, ASTM D2047, Philadelphia.	0
Hunter, R. B. "A Method of Measuring Frictional Coefficients of Walkway Materials," J. Res. Nat. Bur. Standards 5, RF204, August 1974, p. 329.	0
Irvine, C. H. "A New Slipmeter for Evaluating Walkway Slipperiness," American Society for Testing and Materials 7(12), Philadelphia, December 1967, pp. 535-541.	0

	Citation Index Number
Irvine, C. H. "Shoe Sole Slipperiness on Structural Steel," Materials Research and Standards 10, April 1970, pp. 21-22.	0
Irvine, Charles H. "Study and Develop Safer Operational Techniques for Loading and Unloading Automobile Transport Trailers," Liberty Mutual Research Center, Project 68-2, Hopkinton, MA, November 1, 1968.	
Iskrant, Paul, and Sullivan, D. F. "Accidental Falls in Public Places," U.S. Public Health Service, Washington, D.C.	15
Jablonsky, R. D. "Standardization of Test Methods for Measurement of Floor Slipperiness," ASTM, 1978.	20
James, D. I., and Mohsen, R. "Friction: The Importance of Accurately Specifying the Method of Sample Preparation and the Test Conditions," RAPRA Members' Report No. 71.	2
James, D. I., and Newell, W. G. "A New Concept in Friction Testing," RAPRA Members Report No. 20, 1978.	
James, D. I. "Rubbers and Plastics in Shoes and Flooring: The Importance of Kinetic Friction," Rubber and Plastics Assoc. of Great Britain, Shawbury.	0
Johnson, B. S. "A Discussion of Some Factors Influencing Slip Resistance Measurements," Franklin Research Company, Philadelphia, 1958.	0
Kellet, P. H. "Modern Solings in Wear," Shoe and Allied Trades Association, Publication 1P16, 1968.	20
Kobayashi, K.; Miura, M.; Yoneda, Y.; and Edo, K. "A Study of Stability of Standing Posture," Nelson, R. V. and Morehouse, C. A., eds. Biomechanics (8), University Park Press, Baltimore, 1973.	8
Kobayashi, K, and Matsui, H. "Stability of Standing Posture Against an External Force," Biomechanics V-B, University Park Press, Baltimore, 1975.	8

	Citation Index Number
Kroemer, K. H. E., and Robinson, D. E. "Horizontal Static Forces Exerted by Men Standing in Common Working Positions on Surfaces of Various Tractions," Aerospace Medical Research Laboratory Medical Division Wright-Patterson Air Force Base AMRL-TR-70-114, Dayton, January 1971.	7,0
Da Vinici, Leonardo. "Bibliotheque de l'Institut de France," Shoe and Allied Trades Association, MS.E 55R, C.1500.	20
Luitjen, J. A., and Feld, H. A. "Slip REsistance of Soling Materials and Top Pieces," Shoe and Allied Trades Research Assoc., 1973.	20
Mahoney, P. J. "Investigation of Methods for Improving the Frictional Properties of Rubber Used in Footwear," U.S. Army Natick Laboratories Technical Report 72-2-CE, Natick, July 1971, p. 30.	19
Manning, D. P. "Deaths and Injuries Caused by Slipping, Tripping, and Falling," Conference on Slipping, Tripping & Falling Accidents, April 2, 1982.	0
Merscher, J. H. "1972 Rev. of ASTM Std. Method of Test for Stat. Coefficient of Friction of Polish-Coat Floor Measured by James Machine," 59th Annual Meeting Proceedings of Chemical Specialties Manu., December 1972.	19
Miller, J. M. "Safety Research Requirements Relevant to Industrial Floor Friction," Tech. Report, Industrial & Operations Engin., The University of Michigan, Ann Arbor, 1975.	9,0
Morin, A. J. "Nouvellas Experiences sur le Frottement Fait a Metz en 1833," Paris, 1835.	20
Perkins, P. J. "Measurement of Slip Between Shoe and Ground During . . . ," American Society for Testing and Materials, ASTM STP 649, 1978, p. 7187.	0
Perkins, P. J., and Wilson, M. P. "Slip Resistance Testing of Shoes - New Developments," Shoe and Allied Trades Research Association, Kettering, 1982.	0,23
Pooley, R. W. "Measurements of Frictional Properties of Footwear Sole Heeled Materials," ASTM Tech. Publication 649, 1978, pp. 11-20.	20

	Citation Index Number
Rabinowicz, E. "Stick and Slip." *Scientific American* 194(May 1956).	19
Reed, M. E. "Standardization of Friction Testing of Industrial Working Surfaces," U.S. Dept. of H.E.W., Contract No. CDC-99-74-106, Cincinnati, Ohio, August 1975.	0
Riley, M. W., and Arnold, R. C. "Relating Human Static Work of Standing and the Coefficient of Friction between the Shoe and Floor Using a Link-System Model," Annual Meeting Human Factors Society, Inc., Human Factors 22nd, 1978.	0
Rodstein, M. "Accidents Among the Aged," *Safety*, Greater N.Y. Safety Council, 1963.	9
Santos, F. "Factors in Detecting and Correcting Floor Slipperiness," *National Safety News*.	0
Santschi, W. R.; Dubois, J.; and Omoto, C. "Moments of Inertia and Centers of Gravity of the Living Human Body," Wright-Patterson Air Force Base, Aerospace Medical Research Laboratories, AMRS-TDR-63-36, Dayton, 1963.	7
Schallamach, A. "The Load Dependence of Rubber Friction," *Proc. Phys. Soc.* 65(9), September 1952, p. 657.	19
Schuster, K. "Slip - An Investigation of Practical Accident Prevention," *Die Berfsgenossenschaft/Betriebssicherhet*, September 1966.	10
Sigler, P. A. "Relative Slipperiness of Floor and Deck Surfaces - Building Materials and Structures Report," *National Bureau of Standards*, BMS 100, July 1, 1943.	19,0
Snook, S. H.; Irvine, C. H.; and Bass, S. F. "Maximum Weights and Work Loads Acceptable to Male Industrial Workers While Performing Lifting, Lowering, Pushing, Pulling, Carrying, and Walking Tasks," American Industrial Hygiene Conference Paper, Denver, May 1969.	7
"Fundamental Studies of Human Locomotion and Other Information Relating to the Design of Artificial Limbs," U. of California Report to U.S. National Research Council, 1947.	20

	Citation Index Number
"Outline of the Proposed Investigation for Determining the Slip Resistance of Floor Treatment Materials," Underwriter's Laboratory, Subject 410, Chicago, January 1974.	0
Weirich, C. L. "Static Coefficient of Friction Significance of Test Results," 44th Md-Yr Meeting Proceedings of the CSMA, Inc., New York, May 1958.	9,19
Wilson, A. P., and Mahoney, P. J. "Development of Techniques for Evaluating the Frictional Properties of Rubber Sole and Heel Compounds," U.S. Army Natick Laboratories 71(6), Tech. Report 71-6-CE, Natick, May 1970, p. 32.	0

CITATION REFERENCE INDEX

1. Reed, M.E., *Standardization of Friction Testing of Industrial Working Surfaces*, Cambridge: Comstock & Wescott Inc., 1975.

2. James, D.I., "A Broader Look at Pedestrian Friction", *Rubber Chemistry and Technology Review*, 53(1980).

3. Wilson, A. and Mahoney, P., "Measuring Functional Properties of Soles and Heels", *Rubber World*, March 1972.

4. Irvine, C.H., " Evaluation of Some Factors Affecting Measurements of Slip Resistance of Shoe Materials on Floor Surfaces", *Journal of Testing and Evaluation*, 4(2), March 1976.

5. Irvine, C.H., "A New Slipometer for Evaluating Walkway Slipperiness", *Materials and Research Standards*, 10(4), April 1970.

6. Irvine,C.H., "Shoe Sole Slipperiness on Structured Steel", *Materials Research and Standards*, 10(4), April 1970.

7. Kroemer, K.H.E., and Robinson, D.E., "Horizontal Static Forces Exerted by Men Standing in Common Working Positions on Surfaces of Various Tractions", Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Dayton, January 1971.

8. Riley, M.W. and Arnold, R.C., "Relating Human Static Work of Standing and the Coefficient of Friction Between the Shoe and Floor Using a Link-/system Model", Proceedings of the Human Factors Society - 22nd Annual Meeting, 1978.

9. Allcott, G.A., "Slips, Trips and Falls - Working Surfaces and Industrial Stairs", U.S. Dept. of HEW, Morgantown, April 1979.

10. Brungraber, R.J., "A Portable Tester for the Evaluation of the Slip-Resistance of Walkway Surfaces", NBS Technical Note 953, National Bureau of Standards, July 1977.

11. Gavan, F.M. and Vanaman,J.B., "Significant Variables Affecting Results Obtained with the James Machine", *Materials Research and Standards*, November 1968.

12. Ekkebus, C.E. and Kelley, W., "Measurement of Safe Walkway Surfaces", Soap/Cosmetics/Chemical Specialties, February 1973.

13. National Academy of Sciences, "Causes and Measurement of Walkway Slipperiness", NBS Technical Report No. 43, 1961.

14. Pfauth, M.J. and Miller, J.M., "Work Surface Friction Coefficients: A Survey of Relevant Factors and Measurement Methodology", Journal of Safety Research, 8(2), 1976.

15. National Safety Council, "Falls", Education Data Sheet No. 5, revised, Chicago, (date unknown).

16. Santos, Frank., "Factors in Detecting and Correcting Floor Slipperiness", National Safety News, October 1966.

17. "Solving the Problem of Unsafe Surfaces Begins with Selecting Correct Flooring", National Safety News, August 1980.

18. Edosomwan, J.A. and Khalil, T.M., "Accident Prevention in Slips and Falls - A Comprehensive Approach", Professional Safety, June 1981.

19. Brungraber, R.J., "An Overview of Floor Slip-Resistance Research with Annotated Bibliography", NBS Technical Note 895, National Bureau of Standards, Washington, January 1976.

20. James, D.I., "Rubbers and Plastics on Shoes and Flooring: The Importance of Kinetic Friction", Rubber and Plastics Research Association of Great Britain, Shawbury England, 1982.

21. Manning, D.P., "Deaths and Injuries Caused By Slipping, Tripping and Falling Accidents", University of Surrey, April 1982.

22. Cramp, P.A., "Preliminary Study of the Slipperiness of Flooring", National Bureau of Standards, Washington, July 1974.

23. Strandberg, L. and Lanshammar, H., " The Dynamics of Slipping Accidents", Journal of Occupaional Accidents, Amsterdam, 3(1981):153-162.

24. James, D.I. and Newell, W.G., " A New Concept in Friction Testing". Rubber and Plastics Research Association (RAPRA), Report No. 20, Shawbury England, 1978.

25. Fox, W.F., "Body Weight and Coefficient of Friction as Determiners of Pushing Capability", Human Engineering Special Studies Memo No. 17, Lockheed, Georgia, August 1967.

26. Jacobs, N.A.; Skorecki, J.; and Charnley, J., "Analysis of the Vertical Component of Force in Normal and Pathological Gait", Journal of Biomechanics, 13(1980).

27. Draganich, L.F.; Andriacchi, T.P.; Strongwater, A.M.; and Galanti, J.O., "Electronic Measurement of Instantaneous Foot-Floor Contact Patterns During Gait". Journal of Biomechanics, 13(1980).

28. Elftman, H."Forces and Energy Changes in the Leg During Walking",American Journal of Physiology, 125(1939).

29. Adler, S.C. and Pierman, B.C. "A History of Walkway Slip Resistance at the National Bureau of Standards", NBS Special Publication 565, Denver, 1979.

30. Chaffin, D.B. and Andres, R.O. "Evaluation of Three Surface Friction Measurement Devices For Field Use", Center for Ergonomics and Safety, The University of Michigan, September, 1982.

31. Lee, Kwan Suk, "Biomechanical Modelling of Cart Pushing and Pulling", PhD Dissertation, Center for Ergonomics and Safety, The University of Michigan, 1982.

32. Sigler, P.A., "Relative Slipperiness of Floor and Deck Surfaces", National Bureau of Standards, Report BMS 100, July 1943.

33. Underwriters Laboratory, "Outline of the Proposed Investigation for Determining the Slip Resistance of Floor Treatment Materials, Subject 410, January 1974.

34. Anderson, C. and Senne, J., eds. "Walkway Surfaces: Measurement of Slip Resistance", ASTM Special Tech. Pub. 649, 1978.

35. American Society For Testing Materials, "Static Coefficient of Friction of Polish-Coated Floor Surfaces As Measured By The James Machine", ASTM D 2047-75, 1975 (Reapproved 1981).

36. American Society For Testing Materials, "Static Coefficient Of Friction Of Shoe Sole And Heel Materials As Measured By The James Machine", ANSI/ASTM F 489 - 77, 1977.

37. American Society For Testing Materials, "Measuring Surface Frictional Properties Using the British Pendulum Tester", ANSI/ASTM E 303 - 74, 1974, (Reapproved 1978).

38. Johnson, Bayard S. "A Discussion of Some Factors Influencing Slip Resistance Measurements", Franklin Research Company, Philadelphia, May 1958.

39. Miller, James M., "'Slippery' vs. "Slip Resistant' Work Surfaces: The Background For a Regulatory Definition", Dept. of Industrial Engineering, University of Michigan, Ann Arbor, February 1983.

40. Sigler, P.A.; Geib, M.N.; and Boone, T.H., "Measurement of Slipperiness of Walkway Surfaces", Journal of Research, National Bureau of Standards, 40(1948):339-346.

"SLIPPERY" VS. "SLIP RESISTANT" WORK SURFACES: THE BACKGROUND FOR A REGULATORY DEFINITION

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FEBRUARY 1983

This paper and its background research were supported in part by the Directorate of Safety Standards, Occupational Safety and Health Administration, U.S. Department of Labor

ABSTRACT

There has been over fifty years of scattered research into the areas of walking/working surface slipperiness and coefficient of friction(COF) measurement. In spite of this research, numerous standards address slip/fall type accidents only in terms of requiring surfaces to be qualitatively "non slippery". This paper summarizes that literature useful in providing guidelines for establishing quantitative criteria for "slippery" vs. "slip resistant" combinations of surface, shoe, task and contaminant conditions.

Recommendations applicable to standards making organizations are made. Among them are: (a) changing legally inappropriate descriptor terms such as "non-slip" to "slip resistant"; (b) defining "slippery" vs. "slip resistant" in terms of quantitative COF values (i.e.,for persons walking unloaded on level surfaces a COF of 0.5 would be a reasonable standard); (c) modifying standards to emphasize that "slip resistance" requirements may be met more easily by controlling the type shoe, type task, or amount of surface contaminant rather than controlling only the COF of the basic surface and its coating.

Additionally, those questions key to the area and still unanswered are summarized, providing directions into which future research efforts might be directed.

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I. BACKGROUND

A. THE REGULATORY ISSUES OF CONCERN

In at least thirty locations within 29 CFR Parts 1910 and 1926 there exist requirements for employers to provide work surface conditions which will provide protection for workers against slip/fall type accidents. These provisions were adopted almost unchanged from the existing ANSI standards. Most of them place performance type requirements on the work surfaces covered. The types of work surfaces include steps, ladders, walkways, platforms, floors, treads, footwalks, plank walkways, foot pedals, rungs, and decks. The OSHA regulations utilize the mandatory "shall" in describing the type of anti-slip/fall characteristics which such surfaces are to have. This "shall" appears in conjunction with descriptors such as: slip resistant, nonslip, nonskid, non-slippery, anti-slip, safe footing and adequate footing. Many of these terms seem to be currently used almost interchangeably within the OSHA standards. The same type of language occurs to a much less extent within other government and consensual standards.

There is only one location among the OSHA anti-slip/fall type regulations that any quantitative requirements are suggested for determining what might be meant by "non-slip" type descriptors (29 CFR 1910.68 (c)(3)(v)). Therein lies the provision that ..."The upper or working surfaces of the step shall be of a material having inherent nonslip characteristics (coefficient of friction not less than 0.5)...". However, nowhere within the OSHA regulations are there provisions or inclusions by reference of recommended methodologies to be used to make quantitative measurements of a coefficient of friction (COF). Nor are there any guidelines to provide the employer any benchmark information as to what types of surfaces or circumstances would be expected to yield non complying anti-slip/fall conditions. This situation within the standards has lead to the following issues: (1) neither private employers nor government compliance officials are able to interpret and apply those parts of OSHA and other government standards having anti-slip/fall provisions; and (2) OSHA and other government organizations are not in a position to know how to remedy the vagueness of this performance language which exists within their own regulations.

I. BACKGROUND (cont)

B. THE TRADITIONAL RESEARCH QUESTIONS

Since the early 1930's, government and private researchers from the U.S. and Europe have been striving to quantitatively describe the interaction that occurs between the shoe sole (or foot) and surface. These shoe-surface interactions occur for purposes of walking, climbing, turning, pushing, pulling and other tasks. There does seem to be agreement among the researchers that the interactions which occur are a function of the shoe sole, surface, environment, task, and method of shoe surface contact. It is also generally agreed that this interaction causing people to slip is best quantitatively described using coefficient of friction measures. There are a few proponents who would subscribe to the use of subjective ratings by individuals based on the "feeling of slipperiness". The consensus, however, remains that the physically measured coefficient of friction (COF) is closely correlated with the tendencies of people to slip. Given this admission, one's ability to obtain further consensus becomes considerably more difficult. Fifty years of research instead of resolving the issues have often brought foreward inconsistent results and a differing of opinions. The following lists what this author has found to be those questions which have persisted in the past and are of research interest/need yet today:

1. Does walking, turning, climbing, pushing, and pulling involve the static or dynamic COF phenomenon or some combination?
2. Do the COF testing machines used to gather early or recent data measure dynamic or static COF ?
3. Do all shoe-surface combinations have both static and dynamic COF values which are separately identifiable?
4. How does dynamic COF vary with the slipping speed between the shoe sole and surface?
5. Which testing machines can produce the most repeatable and accurate results for laboratory tests or for field tests on in-service work surfaces?
6. What COF values are necessary to counteract the horizontal forces generated by a person's walking, climbing, turning, pushing, pulling, etc.?
7. What COF values are necessary to prevent persons from slipping as a function of the types of tasks performed?
8. What COF values can one typically expect for various combinations of shoe soles, surfaces, and contaminant conditions (oil, water, and dirt) ?

I. BACKGROUND (cont)

C. THE POLICY DILEMMA

The above questions have not been resolved to hardly anyone's satisfaction. Thus, government organizations (i.e. OSHA and DOT) have elected to not promulgate those additional clarifications to their standards which would specify required quantitative COF values for various walking-working-climbing surfaces. The difficult policy question to face becomes: Is the preponderance of factual material now sufficient for more substantive rulemaking on anti-slip/fall provisions within standards?

If the answer is "yes", then as a government policy maker one faces the challenge of being able to establish, modify, clarify or interpret standards in a way which will be viewed by the public as being: (a) effective in reducing slip/fall type injuries; (b) technologically feasible; (c) practically achievable; (d) capable of reasonable enforcement; and (e) not an economic burden to employers.

If the answer to the above policy question is "no", then we must sadly admit that little progress has been made over the past fifty years with respect to COF related accident prevention. As a result of such a negative conclusion, we are admitting the inability to provide assistance to employers who in good faith want to comply if they can only be told what "anti-slip", "non-slip", and "slip resistance" type compliance terms mean. The problem goes beyond employers not knowing how to comply. It extends also to the compliance officers who don't know how to interpret the performance language in these standards for enforcement purposes. The result is that we have contributed little to addressing where one in about every five occupational accidents occurs.

The OSHA administration and other government agencies have understandably not taken a regulatory position with respect to defining what criteria to apply to "slippery" surfaces. The published research information over the years has presented a dilemma because of the legitimate though somewhat academic controversies which have existed. The subjects of these controversies were contained in the eight questions posed earlier.

Philosophically, a policy maker can take the conservative position of being reluctant to recommend action on anything until the "beyond the shadow of the academic doubt" has been satisfied. This position suggests that there is justification to resolve all the controversial issues before an affirmative decision is made to allow humanity to take advantage of existing and available research findings. Such a conservative position is understandably justified in much medical type research. But in the accident prevention area it would seem more rational to encourage the early application of worthwhile research findings. This is particularly so if these findings are likely to bring more immediate injury saving assistance to workers without a significant risk that such application is premature . The danger, of course in any early application is that the research community may find a basis to reverse its initial recommendations or put the policy maker in the embarrasing position of admitting that a "little knowledge was a dangerous thing".

Thus, as a policy maker, the decision to take action based on existing information always carries with it the risk and almost expectation that new developments will make previous decisions look less optimal. Consequently, the insecure manager may prefer to procrastinate , waiting always for more and better information in the future as a rationale for not acting in the present. Politically, this is often a "safer" position if persons are concerned with their own "political occupational safety".

In conjunction with the information brought together in this paper, it will be shown that there is a bases upon which OSHA and other government administrators can begin now to provide further refinements to their slip/fall related standards. One should not fault the OSHA administration for failure to take such steps to date since such refinements could have been but were not provided by the experts having responsibility for the ANSI consensual standards in effect in 1970. If that had been the case, then OSHA would have them in their standards today. (Recall that what consensually existed among the experts in 1970 is what OSHA was forced to promulgate.)

Between 1970 and now there have been efforts by NIOSH and NBS which were particularly intended to help the further development of the COF related OSHA standards and their enforcement. Unfortunately, this research has left OSHA and other governments agencies with two unresolved problems. First, the results of these efforts barely went beyond laying out recommendations for further research. The implication was that such research would be necessary before unattackable decisions leading to supportible regulations could be made. However, a recommendation to do only further research and development leaves a regulatory agency in an awkward position, particularly if there is pressure on an agency to show regulatory progress and that agency has the desire to so respond.

The second problem related to research which OSHA and other government agencies face is their understandable difficulty in integrating the wide breadth of COF research within the literature . To be useful it must be in a form appropriate to use as a basis for making modifications to the current existing slip/fall related standards . This is necessary because of the requirement to have well documented background and justification preambles to accompany any proposed government actions such as rulemaking. Publication in the Federal Register of such is required to allow for critical public review by those affected. An inadequate or inappropriate rationale given for any government action will most assuredly be the subject of challenge through litigation procedures available to the affected public.

Assisting in the resolution of these two above policy type problems facing government agencies is an important objective of this paper. This will be satisfied in part by showing: (a) that the "preponderance of evidence" is sufficient at this time to initiate additional "standards related activities" in the slip/fall area; (b) that the literature can be integrated into a form that is useful for purposes of justifying such proposed actions and; (c) that as additional research findings become available they can and should be integrated systematically into these standards. (To prevent any misunderstandings, this author means by "standards related activities" not only modifications to regulations themselves but also any interpretive, directive, explanatory, or other informational material which might be developed by government sources to assist employers in complying with standards).

II. CONCLUSIONS FROM THE LITERATURE

A. QUALITATIVE RECOMMENDATIONS

Over the past twenty-five years there have been six key publications which in this author's opinion best contribute and capture the history of COF research. They also provide significant regulatory policy implications. These notable documents are as follows: Federal Construction Council, National Academy of Sciences (1961) [Ref#13]; Reed (1975) [Ref#1]; Pfauth and Miller (1976) [Ref#14]; Brungraber (1976) [Ref#19]; Adler and Pierman (1979) [Ref#29]; and James (1980) [Ref#2]. (Complete citations for these appear at the end of this report.)

Collectively, these authors have been reluctant to recommend that the government promulgate standards tied to either a specific COF value or to a specific definition of "slippery". As indicated earlier, their suggestions are directed towards the need to do additional research and development in the area. This can be seen by the following representative conclusions and recommendations selected from the six references above. While the chronology of some of these articles goes back twenty years, they still describe the current position of the COF state of the art. The reader will note that most of the following quotations address issues related to the eight research questions previously presented.

1. FEDERAL CONSTRUCTION COUNCIL, National Academy of Sciences (1961), [Ref# 13], page 12

"Select or develop a simple, portable device for field use in measuring slip-resistance."... "Develop slip-resistance standards which consider locations and conditions of use."..."Develop a set of standard reference surfaces which are economically reproducible; usable under field or laboratory conditions, and have long term stability/durability or are expendable."... "Recommend maintenance procedures."

2. REED, Comstock and Wescott, Inc. (1975), [Ref# 1], page 54

"From results obtained using the Universal Friction Testing Machine , it was concluded that the COF for RMA rubber are extremely sensitive to the velocity at which the COF is measured."..." The COF of leather is also sensitive to velocity but is less sensitive then rubber on an absolute scale."..." Leather produces dynamic values of COF which would generally be considered unsafe for the use of leather as the heels of shoes."

3. PFAUTH AND MILLER, University of Michigan, (1976), [Ref#14], page 89

"Additional research is needed to determine: the forces that the foot exerts during various manual materials handling tasks; the additional slipping risk that occurs with increased age and/or decreased physical ability; the effect of different shoe designs ; the friction requirements of mobile machinery; and what role psychological factors and preconceived biases play in slip type accidents."

4. BRUNGRABER, National Bureau of Standards, (1976), [Ref#19]

a. GRAVITY OF THE PROBLEM ,page 2
"The seriousness of this (slip) problem has resulted in continuing research by the manufacturers of floor waxes and polishes, many shoe manufacturers and users, insurance laboratories and numerous government laboratories (state, federal and foreign)."

b. KINESIOLOGY AND ANTHROPOMETRY, page 3
"It is clear that a walking surface can be too slippery to permit safe walking. It may also be that a walking surface could be too slip resistant to permit safe, convenient walking."..."Thus, as was claimed by James, the most significant parameter controlling the slip-resistance of floors is the static coefficient of friction."

c. THE GENERAL STUDY OF FRICTION, page 4
" A friction problem more directly related to floors is the increase in the static coefficient of friction with the increase in time delay between the application of the normal loads and the tangential or sliding load....this is caused by adhesion which in many cases is enhanced by the presence of water between the sliding surfaces. This may well be the explanation for the increase in coefficient of friction of leather soles by wetting that has been observed by many investigators....This points up the need for a friction measuring device that closely approximates the time delay that is representative of a normal step that is generally repeatable."

d. APPRAISAL OF METHODS FOR DETERMINING FLOOR SLIP RESISTANCE, page 5

"The pendulum type, as represented by the Sigler and the British Portable Skid Tester measures only the dynamic friction and this as some sort of integrated function resulting in a measured energy loss of the pendulum...The dynamic coefficient of friction is not of prime importance in controlling slip resistance.... The Hunter device has the disadvantage that it measures the dynamic friction... The James machine does measures the static friction but for some reason, not explained in James' article, the final version of his device is strictly a laboratory machine suitable only for evaluating floor materials, not floors.....Many investigators have shown that within rather broad limits, the coefficient of friction between typical shoe and flooring materials is not sensitive to variations in contact pressure."

e. GUIDE FOR SELECTION OF SLIP-RESISTANCE CRITERIA, page 7

"There are three sources of information that can be used to select these values: (1) experimental kinesiology or measurement of the forces exerted by the shod foot upon the floor, (2) anthropometry or geometry of the walking body, and (3) friction measurements made on walkway surfaces having known safety records. In setting recommended values for floor slip-resistance or static coefficient of friction it may well be that for certain walking maneuvers the friction could be too high and thus recommendations should be in the form of both upper and lower limits."...

"Unfortunately the only fundamental evaluations of the static coefficient of friction have been made with the James machine and thus were made on flooring materials, not floors, and under controlled laboratory conditions, not in the field. Most field measurements have been made with either pendulum devices, such as the Sigler or the British Portable Skid Tester, or with the drag type devices such as the Horizontal Pull Slipmeter."

f. LEGAL ASPECTS AND STATUS OF SPECIFICATIONS, page 8

"There are several industries interested in the legal aspects of floor slip-resistance: the flooring manufacturers, the shoe manufacturers, the underwriters who insure buildings and the floor wax and polish manufacturers."...

"The government specifications have been primarily developed by the military and are quite stringent, requiring that the coefficient of friction be as high as 0.7 in some cases. The other major contribution to floor slip resistance specifications has been a combined effort of the committee D21 of ASTM and the Scientific Committee Of the Wax Division of the Chemical Specialties Manufacturer's Association (CSMA).There has been considerable common membership in these two bodies and a great deal of cooperation between them... culminating in the recently published revision of the Standard Method of Test for Static Coefficient of Friction of Polish Coated Floor Surfaces as Measured by the James Machine (D2047-75). This revision now states "Floor polishes having a coefficient of static friction, measured by this method, of not less than 0.5 traditionally have been recognized as providing nonhazardous walkway surfaces. This value of not less than 0.5 meets the requirements for compliance to Rule 5 on 'The Use of the Terms Slip Retardant, Slip Resistant or Terms of Similar Import,' of the Proposed Trade Practice Rules for the Floor Wax and Floor Polish Industry as issued by the Federal Trade Commission on March 17, 1953."

5. ADLER AND PIERMAN, National Bureau of Standards, (1979), [Ref # 29] , pages 2,23

"Existing standards and codes for walkway surfaces are generally vague and difficult to enforce since they lack quantitative definition of acceptable levels of slip resistance. The Center for Building Technology (National Bureau of Standards) is advancing research to permit the inclusion of quantitative criteria for slip-resistance now missing from voluntary standards and mandatory regulations."...

"An extensive series of tests of commonly encountered walking surfaces has been conducted at selected locations including ...data for common floor materials including polished and worn wood, terrazo, marble, concrete and vinyl-asbestos tile will be provided. Both wet and dry measurements have been completed and a report will be published in 1979." [Author's note:I do not believe that the results of this study had been made available as of November 1982]

6. JAMES, Rubber and Plastics Research Association of Great Britain, (1980), [Ref # 2], page 538

"For safety the coefficient of friction should increase as velocity increases, so that sudden and uncontrollable slipping cannot occur."...
"Few of the test machines at present used for pedestrian friction are adequate for their purpose. Two types of testers are needed (a) a laboratory test for quality control of either footwear materials or flooring materials as appropriate, (b) a portable tester for checking installed floors and the effect of floor treatments. In either case only instruments capable of measuring over a range of test conditions, in particular a range of velocities, should be considered, In comparative tests some form of practical service test, such as the SATRA ramp, should be included. Whether any test has been accepted as a Standard Method by any country is irrelevant and acceptance of a test by a Standards Committee should not be taken as a measure of its correctness."...
"It is suggested that for quality control purposes some universally available standard material, such as plate glass be chosen, the appropriate friction characteristics for safety on such a surface being established initially by practical experiment....it is also necessary to define some universally available contaminant which bears some resemblance to the dirt or dust picked up by shoe soles in practice."

Since the above quotations concisely summarize the state of the art from a qualitative viewpoint, further comments are unnecessary at this time. Those aspects of the above which relate particularly to the regulatory interests of this paper will be utilized in the last section which gives recommendations.

B. QUANTITATIVE RESULTS

Among the areas raised by the eight questions presented earlier, three must be adequately addressed before any further progress in standards or regulatory activities can proceed. They are question numbers:

6. What required COF values are necessary to counteract the horizontal forces generated by a person's walking ?
7. How do required COF values vary as a function of other than walking type tasks, i.e., pushing and pulling ?
8. What COF values can one typically expect for various combinations of shoe soles, surfaces, and contaminant conditions (oil, water, and dirt)?

Many practitioners would argue that it is of equal importance to answer the questions about dynamic vs. static COF, and what type COF measurement machine to use to achieve the most accurate and repeatable results. As it will be seen , these other issues are not considered to be of the same level of priorty to this author. To address these questions, a tabular summary has been developed. It integrates a variety of other authors' key quantitative findings and recommendations. They appear within TABLE 1: QUANTITATIVE COF RESULTS AND RECOMMENDATIONS FROM SELECTED AUTHORS. (Due to its length, TABLE 1 follows the main body of this paper).

1. FORMAT FOR THE TABULAR SUMMARY

Table 1. has been divided into the categories which follow. Note that identifying certain historic studies as being in a "static" or "dynamic" category is somewhat arbitrary, since by today's thinking many findings do not necessarily fall clearly into one category or the other.

A. "STATIC" COF RESULTS - HUMAN SUBJECTS USED
    1. REQUIRED COF TO WALK MEASURED
    2. MAXIMUM OR RANGE OF FORCE CAPABILITY MEASURED
B. "STATIC" COF RESULTS - MATHEMATICAL/COMPUTER MODELS USED ONLY (NO SUBJECTS)
C. "STATIC" MEASUREMENT OF SURFACE/SOLE COMBINATIONS (NO SUBJECTS)
D. "DYNAMIC" COF RESULTS INCLUDED IN DATA
E. REQUIREMENTS/RECOMMENDATIONS IN EXISTING STANDARDS

2. CONCLUSIONS FROM THE TABULAR SUMMARY

The overview of results which is provided by Table I. concentrates on first the minimally required COF to prevent persons from slipping on working/walking surfaces. Next, results are given for what COF exists or what would be expected to exist as a function of the type of surface and its condition - wet, dry, clean, dirty, etc.. Based on a review of that table and the literature from which it has come this author boldly concludes the following:

1. The minimum required static COF for normal pace walking unloaded on a level surface ranges between 0.2 and 0.4 depending on the particular author's research methodology and to some extent on the type of walking - straight or turning left or right.

2. The required COF to prevent slipping is highly task dependent. Walking up or down ramps, pushing or pulling loads, or even fast walking and running will require COF values much higher than that required for unloaded normal pace walking on a level surface. For certain tasks, values of COF as high as 0.8 - 0.9 might regularly be required.

3. Leather soles/heels are almost always much poorer than rubber in antislip characteristic qualities. The decrease in COF value due to leather may be as much as 0.5 under comparable conditions.

4. Nearly all dry and clean combinations of shoes and surfaces have COF values greater than 0.5 while only selected wet combinations of shoes and surfaces result in a COF value greater than 0.4.

5. The most common recommended COF by standards organizations and by individual authors is 0.5. This value seems reasonable since it allows a small margin of safety over and above the 0.4 COF which was often cited as needed for walking. None of these authors suggested that their recommendations be extended to or would be sufficient for other than walking types of tasks.

Having reviewed the qualitative and quantitative findings in the literature, and having drawn some conclusions from same, this paper now turns to the application of some of these conclusions to future governmental regulatory activity.

III. RECOMMENDED APPLICATION TO REGULATORY ACTIVITY

A. A DEFINITION OF SLIPPERY

"Slippery" must be defined in terms of the task being performed in addition to the performance interactions which occur among shoes, surfaces and contaminants. Thus, the following "performance" definition is proposed by this author: A "slippery work surface" is defined as that combination of (1) a host transient surface (such as a shoe or tire), (2) an agent structural surface (such as a floor, step, or ramp) , and (3) contaminant conditions (such as water, oil or dirt), all of which together have the propensity to cause the initiation and/or promotion of a sliding between the host and agent surfaces during the performance of actual or anticipated tasks. Reconize that this definition is proposed as being technically correct and universally applicable. Simplified versions which might include quantified criteria would of course be used for a specific application.

As a start in providing such quantified criteria the following is suggested. For the walking unloaded task on level surfaces, a "static" COF of about 0.5 for the shoe/surface interaction combination would seem to be consensually acceptable as a quantitative standard. It is also an upper limit for what initial research has shown to be required by the physical walking process. One cannot utilize this value without at the same time pointing out the limitations of the research from which it comes. In particular, these studies do not include people as they iniitiate or terminate walk type tasks. Nor to this writer's knowledge have tasks involving the carrying of heavy objects been included. Rather the COF value of 0.5 should primarily be thought of in terms of traditional pedestrian "in movement" type walking unloaded tasks. Higher values of required COF can probably be anticipated as "load carrying" type research is eventually done. Any regulation utilizing a 0.5 COF must be capable of being integrated into those future requirements which will be justifiable as other task-related research findings are available. This author does not recommend waiting on such findings before initiating rulemaking which can start to change the incomplete and unclear regulatory provisions now existing.

Another aspect of any definition should be the explanatory material which accompanies it. Such explanations can assist the reader in understanding the specific limited applications for which it was intended. They can also provide indications as to where research activities in an area might eventually lead a standard or the criteria specified therein. In any document having a definition/standard for a "slippery work surface" one should include some attention to the emerging role that dynamic friction may be taking in future standards. For example, combinations of conditions which yield high dynamic COF or an increasing dynamic COF with velocity should eventually be permitted in lieu of a fixed static COF standard. The above definition for "slippery" provides for this type of alternative "performance". It will also hopefully encourage new materials technology which addresses the role of dynamic COF in "stopping an initiated slip from continuing".

The above definition is also generically broad by intent. While this paper addresses "slippery" in relation to slip/fall accidents, the definition is also applicable to other types of slippage which may lead to accidents. For example, the forklift truck which can slip out of control into people, structures, or machines is another type of potentially dangerous work situation. Neither research nor standards in this country have given attention to these other types of slipping hazards in the work environment. Nor have they addressed slipping hazards in the consumer environment such as the possibility of a portable cooking appliance slipping off a countertop and burning the user or the user's child. The primary research regarding slipping has almost exclusively addressed the pedestrian walking type situation. However, it is the non pedestrian and even non occupational areas wherein substantial concern should also be focused. While falling outside the scope of this paper's objective, they remain significant to this author's research interests.

B. THE TERM "NON-SLIP" VS. "SLIP RESISTANT"

The Federal Trade Commission, by "Rule 5", made it clear that terms such as "non-slip" and "non-skid" are not to be used to describe surfaces or surface coatings. Such terms are inappropriate because from a strict legal interpretation they suggest that a person will never slip on such surfaces no matter what the conditions or circumstances. Many of these types of terms are currently used frequently in OSHA and ANSI standards. The FTC Rule 5, as it is called, indicates that such languuse use is inappropriate. Therefore, it would be preferred , if not mandatory , to eliminate all use of such terms in favor of descriptors such as "slip resistant", "slip retardant" or "skid-resistant". These would all in turn be synonymously defined in terms of those circumstances falling outside the earlier definition proposed for "slippery".

From the same legal source there is also some precedent for the use of a static COF of 0.5 as the quantitative dividing line between "slippery" and "slip resistant". Recall that this value was initially determined from walking type research. However, it would not be surprising to find this same value misapplied during litigation to other than walking type accidents. It would seem, thus, that there is some urgency to thoroughly research the required COF for many other types of work (and non-work) tasks, besides walking. The default alternative to not researching and recommending is that the number of 0.5 be universally thrust upon us for all conditions and tasks.

C. FIELD DETERMINATION OF COEFFICIENT OF FRICTION

The field determination of COF values may never be an issue satisfactorily resolved if "on the spot" measurements of COF are regularly required for all employers. Friction measuring devices, even the portable ones, are more like research instruments than like "off-the-shelf" easy to use quick reading digital gauges. One should expect these devices in their present form to have applications limited to the more sophisticated employers and other users.

On the positive side, this author believes that it is reasonable to provide for employers tabularized quantitative guidelines for what values of COF could be approximately expected. These can be developed as a function of type shoe sole, heel, surface, and contaminant conditions. Approximating a COF value using tables may seem overly simple in light of the efforts to develop universal friction measurement devices. It would probably not satisfy the accuracy criteria of the purists. However, in a practical way this approach may be sufficient for a great many employers' situations. It would certainly be a big gain over the current situation of their knowing nothing about how to comply! These tables in a limited way exist within the literature as scattered research results by different authors using different measurement devices . A deliberate effort to bring these findings together in a form useful to employers would seem justified. They would ultimately be more useful cost/benefit speaking than the development or underwriting of specific machines which might be used by all employers to measure their specific work surface COF values. In a limited form the proposed tables could even now be included as informational material within or used as appendices to safety standards. It is emphasized that these values would only yield the approximate COF existing. In so doing, the employer might then know the likelihood that his situation would be considered hazardous as compared to some quantitative criteria within a standard.

III. APPLICATION TO REGULATORY ACTIVITY (cont)

D. REGULATORY/COMPLIANCE ACTIONS RECOMMENDED

The above material suggests a given shoe, surface, or contaminant condition has a particular COF associated with it; and on the other hand a given task will have a minimum required COF to accomplish it without slipping. This is really a trivial restatement of the laws of physics which insist that in order to keep a body in equilibrium, forces acting on it from one direction must be countered with an equal and opposite force. Therefore, standards for COF can be written as requirements dependent on the type of task to be performed (the originating force) or on the COF ability of the shoe/surface combination to exert an equal and opposite force (the reactionary force). Such a standard could allow for an employer to achieve compliance by either: (a) controlling the combination of shoe/surface/contaminant condition to which the worker is exposed; or (b) controlling the type of task being performed with a given shoe/surface/contaminant condition, which condition of course has a particular COF associated with it. In other words The standards making body should recognize either method of control as achieving compliance.

These suggestons for alternative approaches to standards writing lead to the following list. It summarizes those points presented earlier which could be acted upon by government regulators without any significant additional research.

1. Provide a general duty type provision defining a "slippery work surface".

2. Define "slippery" vs. "slip resistant" surfaces using a quantitative static COF value. This, for level surfaces subjected to employees walking unloaded, could be reasonably placed at 0.5. (Loaded vs. unloaded will have to be defined.)

3. Change inappropriate descriptor terms in standards such as "non-slip" and "non-skid" to "slip resistant".

4. Modify standards to emphasize that COF or "slip resistant" requirements can be met sometimes more easily by controlling the type shoe, type task, or amount of contaminant as an alternative to controlling only the COF of the basic structural work surface and its coating.

5. Develop informational material to insert within standards or their appendices to indicate approximately: (a) what COF is required as a function of the task being performed, and (b) what COF can be expected for a given type of shoe sole/heel, work surface/coating, and contaminant condition.

6. Emphasize within the standards the serious slip hazard which most assuredly will exist when work surfaces become contaminated with water, oil, and dirt because of poor process control or housekeeping.

7. Suggest to employers the difficulty they will have complying with the standard if all leather shoe soles and heels are permitted on wet or contaminated surfaces.

This paper has tried to focus on how to define "slippery" and what government regulatory activity could be undertaken at this time with a minimum amount of additional research and development work. Some of the above recommendations may seem innovative within the rulemaking context as opposed to how other authors have been approaching the subject. Hopefully, this approach will promote some progress in preventing slip/fall type work surface accidents and be considered favorably by the constituent that which would ultimately be affected by its implementation.

IV. TABLE 1

QUANTITATIVE COF RESULTS AND RECOMMENDATIONS FROM SELECTED AUTHORS

TABLE I

QUANTITATIVE COF RESULTS AND RECOMMENDATIONS FROM SELECTED AUTHORS

A. "STATIC" COF RESULTS - HUMAN SUBJECTS USED

1.REQUIRED COF TO WALK MEASURED

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
University of California	1947	41		f = 0.5 needed at heel touch down	Lapse time photography revealed no slip (no dynamic movement) during walking.
in Brungraber	1976	19	08		
Cunningham	1950	42		"f" For walking: Level: .25-.33 Up Stairs: .15 Down Stairs: .15 Up Ramp: 0.3 Down Ramp: 0.4	Subjects were used but measurement device not specified. Research aimed at artificial limb design.
in Brungraber	1976	19	15		
National Bureau of Standards	1951	43		f = 0.2 at heel touch down. f = 0.4 at toe leaving.	Electronic "stepmeter" measured subjects walking ; similar to current force platforms.
in Brungraber	1976	19	17		
Johnson	1958	38	204	f = 0.2-0.3 for walking f > 0.5 recommended	Electronic "stepmeter" designed by NBS used. This was first publication listing f>0.5 as recommended standard.
Harper	1961	44		.36 straight walk .40 turn, left foot .36 turn, right foot	Measurements made using force plate which subjects walked over.
in Brungraber	1976	19	20		
Schuster	1966	45		f > 0.6 on 15% grade	Used "inclined plane" tester to conclude subjects felt surface to be "slippery" if f>0.6 while walking up and down 15% incline.
in Brungraber	1976	19	13		
Carlsoo	1972	46		f = .23 mean for walking f > 0.5 recommended	Force plate used to measure 100 subjects walking. Recommended value to make slipping "non existent".
in Brungraber	1976	19	23		
Perkins	1978	48		Landing phase: Avg =.24, Max =.28 Take-off phase:	Force plate tests with subjects walking. Values are for H/V
in James	1982	20	13		

TABLE 1 (CONTINUED)

A. STATIC" COF RESULTS - HUMAN SUBJECTS USED
2.MAXIMUM OR RANGE OF FORCE CAPABILITY MEASURES

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
Kroemer	1971	7	25	Max. static push/ pull capability for given COF range: 0.2 <f <0.3 25 lb f = 0.6 45 lb f > 0.9 70 lb	COF values were arbitrarily fixed to determine how much push-pull force could be exerted by subjects at that level of COF.
Lee	1982	31	132	f = 0.2-0.8 depending on force exerted and height of handle used for push/pull test.	Force platform used to measure H/V ratios associated with range of push/pull forces at different handle heights.

B. "STATIC" COF RESULTS - MATHEMATICAL/COMPUTER MODELS USED ONLY

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
Ekkebus	1973	12	44	f = .298-.44 based on biomechanical model's stride	Author accepts f > 0.5 as "conservative" recommendation for a standard with a "reasonable" safety factor.
Riley	1978	8	13	f = .378 male f = .418 female	Friction value below which the hip moment can no longer be zero, based on link system biomechanical model.

TABLE 1 (CONTINUED)

C. "STATIC" MEASUREMENTS OF SURFACE/SOLE COMBINATIONS (NO SUBJECTS)

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
Sigler (NBS)	1943	32	12	Suggested "good antislip coefficient" would be $f > 0.4$ for rubber heels (based on heels and floors available at time of test).	About 30 floor materials were tested in lab against leather vs. rubber heels under dry, wet, clean, dirty,and soapy conditions. Same pendulum tester used to measure effects of wax finishes.
Sigler (NBS)	1948	40	346	Suggested "slippery" condition exists if "antislip" coefficient $f < 0.4$. Leather almost always poorer than rubber. Most dry combinations result in $f > 0.5$. Few combinations have $f > 0.4$ when wet.	Portable pendulum tester used on actual in-service floors with some lab tests also. Twenty surfaces tested wet and dry against leather vs. rubber heels. Some authors (i.e. James) contend this pendulum tester actually measures dynamic friction. Thus the Sigler "antislip" coefficient is really a dynamic COF value.
Kroemer	1971	7	31	"Slider" type sled tester used. Overall means: f (dry) = .69 f (soiled) = .52	Twelve flooring specimens in combination with eight soling specimens were measured. Dynamic COF was found to be close to static during preliminary tests. Therefore, only static was measured in tests. Soiled conditions defined as "oil and water.
Chaffin	1982	30	41	Range f = 0.4-0.8 with up to 40% differences among readings for three COF machines. Wetted surfaces had highest variability among machines used.	Ten floor surfaces in six plants studied using leather and combination soles. Bigfoot, Slipometer, and Brungraber machines compared including some lab comparisons.

TABLE 1 (CONTINUED)

D. "DYNAMIC" COF RESULTS INCLUDED IN DATA

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
Barrett in Brungraber	1956 1976	47 19	 11	f = 0.497 for walking f > 1.077 for running	Analytically determined as being required using "neutrally suspended table".
				f(static) = 0.6-0.7 f(dynamic) = 0.7-0.8	Recommended COF for ideal soling material under normal dry and wet conditions.
James	1982	20	20	Kinetic COF should rise above 0.6 at some low velocity.	Pendulum tester used to measure "dynamic" COF. Previous authors (i.e. Sigler) considers this apparatus as a measure of what he calls the "antislip coefficient". Tests for rubber static COF were unrepeatable. This suggested that rubber has only a dynamic COF which is dependent on velocity. Recommends that best static test is ramp test.

TABLE 1 (CONTINUED)

E. REQUIREMENTS/RECOMMENDATIONS IN EXISTING STANDARDS

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
Bunten in James	1967 1982	49 20	 14	Skid Resistance Reading — Floor Conditions f < 19 Dangerous f=20-39 Marginal f=40-74 Satisfactory f > 75 Excellent	Greater London Safety Council Architects Dept. used skid test (ramp) to establish these limits.
Underwriters Laboratory Subject 410	1974	33	--	f > 0.5 as measured by James machine required as minimum "slip resistance" criteria.	Proposed method for determining slip resistance of Floor Treatment Materials (FTM) 1,2,3,4,5,6. Also applies to Walkway Construction Materials (WCM).
Edosomwau	1981	18	31	f > 0.5	Based on other references, author cites f > 0.5 as being common divide point between slippery and non slippery.
				f > 0.7	Some military standards require f > 0.7.
American Society for Testing Materials ASTM-D2047-75	1975	35	1	f > 0.5	"Floor polishes having a static COF as measured by this method (using the James machine: Author) of not less than 0.5 traditionally have been recognized as providing nonhazardous walkway surfaces".

Author	Date	Rf	Pg	Coefficient Value "f"	Comment
American Society for Testing Materials ANSI/ASTM-0489-77	1977	36	--	No value given	Method for measuring sole and heel materials using James machine. Standard makes no statement as to an acceptable value nor that this method corresponds to a particular type of friction coefficient.
American Society For Testing Materials ANSI/ASTM E303-74	1978	37	--	No value given	Method for measuring surface "frictional" properties using British Pendulum Tester. No values are given for what are acceptable results.

__Table Explanation__

__Coefficient Value "f"__: Depends on the particular author's data as to its meaning; generally refers to "static" coefficient of friction; it is also called "slip resistance criteria" and "anti-slip coefficient". Where it means dynamic COF it is so noted; machine used to collect data critical in establishing meaning of "f" value.

__Rf__: Number referring to "References" listed in this paper.

V. REFERENCES

1. Reed, M.E., *Standardization of Friction Testing of Industrial Working Surfaces*, Cambridge: Comstock & Wescott Inc., 1975.

2. James, D.I., "A Broader Look at Pedestrian Friction", *Rubber Chemistry and Technology Review*, 53(1980).

3. Wilson, A. and Mahoney, P., "Measuring Functional Properties of Soles and Heels", *Rubber World*, March 1972.

4. Irvine, C.H., " Evaluation of Some Factors Affecting Measurements of Slip Resistance of Shoe Materials on Floor Surfaces", *Journal of Testing and Evaluation*, 4(2), March 1976.

5. Irvine, C.H., "A New Slipometer for Evaluating Walkway Slipperiness", *Materials and Research Standards*, 10(4), April 1970.

6. Irvine,C.H., "Shoe Sole Slipperiness on Structured Steel", *Materials Research and Standards*, 10(4), April 1970.

7. Kroemer, K.H.E., and Robinson, D.E., "Horizontal Static Forces Exerted by Men Standing in Common Working Positions on Surfaces of Various Tractions", Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Dayton, January 1971.

8. Riley, M.W. and Arnold, R.C., "Relating Human Static Work of Standing and the Coefficient of Friction Between the Shoe and Floor Using a Link-/system Model", Proceedings of the Human Factors Society - 22nd Annual Meeting, 1978.

9. Allcott, G.A., "Slips, Trips and Falls - Working Surfaces and Industrial Stairs", U.S. Dept. of HEW, Morgantown, April 1979.

10. Brungraber, R.J., "A Portable Tester for the Evaluation of the Slip-Resistance of Walkway Surfaces", NBS Technical Note 953, National Bureau of Standards, July 1977.

11. Gavan, F.M. and Vanaman,J.B., "Significant Variables Affecting Results Obtained with the James Machine", *Materials Research and Standards*, November 1968.

12. Ekkebus, C.E. and Kelley, W., "Measurement of Safe Walkway Surfaces", *Soap/Cosmetics/Chemical Specialties*, February 1973.

13. National Academy of Sciences, "Causes and Measurement of Walkway Slipperiness", NBS Technical Report No. 43, 1961.

14. Pfauth, M.J. and Miller, J.M., "Work Surface Friction Coefficients: A Survey of Relevant Factors and Measurement Methodology", Journal of Safety Research, 8(2), 1976.

15. National Safety Council, "Falls", Education Data Sheet No. 5, revised, Chicago, (date unknown).

16. Santos, Frank., "Factors in Detecting and Correcting Floor Slipperiness", National Safety News, October 1966.

17. "Solving the Problem of Unsafe Surfaces Begins with Selecting Correct Flooring", National Safety News, August 1980.

18. Edosomwan, J.A. and Khalil, T.M., "Accident Prevention in Slips and Falls - A Comprehensive Approach", Professional Safety, June 1981.

19. Brungraber, R.J., "An Overview of Floor Slip-Resistance Research with Annotated Bibliography", NBS Technical Note 895, National Bureau of Standards, Washington, January 1976.

20. James, D.I., "Rubbers and Plastics on Shoes and Flooring: The Importance of Kinetic Friction", Rubber and Plastics Research Association of Great Britain, Shawbury England, 1982.

21. Manning, D.P., "Deaths and Injuries Caused By Slipping, Tripping and Falling Accidents", University of Surrey, April 1982.

22. Cramp, P.A., "Preliminary Study of the Slipperiness of Flooring", National Bureau of Standards, Washington, July 1974.

23. Strandberg, L. and Lanshammar, H., " The Dynamics of Slipping Accidents", Journal of Occupaional Accidents, Amsterdam, 3(1981):153-162.

24. James, D.I. and Newell, W.G., " A New Concept in Friction Testing". Rubber and Plastics Research Association (RAPRA), Report No. 20, Shawbury England, 1978.

25. Fox, W.F., "Body Weight and Coefficient of Friction as Determiners of Pushing Capability", Human Engineering Special Studies Memo No. 17, Lockheed, Georgia, August 1967.

26. Jacobs, N.A.; Skorecki, J.; and Charnley, J., "Analysis of the Vertical Component of Force in Normal and Pathological Gait", Journal of Biomechanics, 13(1980).

27. Draganich, L.F.; Andriacchi, T.P.; Strongwater, A.M.; and Galanti, J.O., "Electronic Measurement of Instantaneous Foot-Floor Contact Patterns During Gait". Journal of Biomechanics, 13(1980).

28. Elftman, H."Forces and Energy Changes in the Leg During Walking",American Journal of Physiology, 125(1939).

29. Adler, S.C. and Pierman, B.C. "A History of Walkway Slip Resistance at the National Bureau of Standards", NBS Special Publication 565, Denver, 1979.

30. Chaffin, D.B. and Andres, R.O. "Evaluation of Three Surface Friction Measurement Devices For Field Use", Center for Ergonomics and Safety, The University of Michigan, September, 1982.

31. Lee, Kwan Suk. "Biomechanical Modelling of Cart Pushing and Pulling", PhD Dissertation, Center for Ergonomics and Safety, The University of Michigan, 1982.

32. Sigler, P.A. "Relative Slipperiness of Floor and Deck Surfaces", National Bureau of Standards, Report BMS 100, July 1943.

33. Underwriters Laboratory, "Outline of the Proposed Investigation for Determining the Slip Resistance of Floor Treatment Materials, Subject 410, January 1974.

34. Anderson, C. and Senne, J., eds. "Walkway Surfaces: Measurement of Slip Resistance", ASTM Special Tech. Pub. 649, 1978.

35. American Society For Testing Materials, "Static Coefficient of Friction of Polish-Coated Floor Surfaces As Measured By The James Machine", ASTM D 2047-75, 1975 (Reapproved 1981).

36. American Society For Testing Materials, "Static Coefficient Of Friction Of Shoe Sole And Heel Materials As Measured By The James Machine", ANSI/ASTM F 489 - 77, 1977.

37. American Society For Testing Materials, "Measuring Surface Frictional Properties Using the British Pendulum Tester", ANSI/ASTM E 303 - 74, 1974, (Reapproved 1978).

38. Johnson, Bayard S. "A Discussion of Some Factors Influencing Slip Resistance Measurements", Franklin Research Company, Philadelphia, May 1958.

39. Miller, James M. "A Bibliography of Coefficient of Friction Literature Relating to Slip Type Accidents", Dept. of Industrial Engineering, University of Michigan, Ann Arbor, February 1983.

40. Sigler, P.A.; Geib, M.N.; and Boone, T.H., "Measurement of Slipperiness of Walkway Surfaces", Journal of Research, National Bureau of Standards, 40(1948):339-346.

41. University of California, "Fundamental Studies of Human Locomotion and Other Information Relating to the Design of Artificial Limbs", Report to National Research Council, 1947.

42. Cunningham, D.M. "Components of Floor Reaction During Walking", Institute of Engineering Research, University of California, November 14, 1950.

43. National Bureau of Standards, "Electronic Step-meter Reveals Mechanics of Walking", Technical News Bulletin, 1951,35(4),50.

44. Harper, F.C., Warlow, W.J. and Clark, B.L. "The Forces Applied to the Floor by the Foot in Walking", National Building Studies Research Paper #32, Department of Scientific and Industrial Research, Building Research Station, London, 1961.

45. Schuster, K. "Slip - An Investigation of Practical Accident Prevention", Die Berufsgenossenschaft, Betriebssicherheit, September 1966.

46. Carlsoo, Sven, "How Man Moves, Kinesiological Methods and Studies", Heinemann:London, 1972.

47. Barrett, G.F.C. "Observations on the Coefficient of Friction of Shoe Soling Materials", Rubber Journal, December 1, 1956.

48. Perkins, P.J. "Measurement of Slip Between the Shoe and Ground During Walking", American Society of Testing Materials, Special Technical Publication #649, 1978,p.71.

49. Bunten, J. "Friction Measurements on Soles and Heels with Particular Reference to Women's Top-Piece Materials", SATRA Publication TM 1355, 1967.