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# FLOOR/SHOE SLIP RESISTANCE MEASUREMENT\*

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*A variety of slip measurement devices exist that provide estimates of both static and dynamic coefficient-of-friction (COF) values between one's shoes and the floor. Unfortunately, different shoe sole/heel materials, floor conditions, and contaminants will affect the tests in ways that result in widely varying COF estimates. This paper reviews the basic physics of such tests and describes a set of experiments to determine the static and dynamic COF values under operating conditions known to exist in different jobs. The results define a set of conditions wherein low (hazardous) COF values would exist (e.g., hard Neolite™ shoe material in contact with a wet, smooth walking surface). The results also question the use of light-load testing devices and static and slow speed reference COF values in the literature.*

**L**oss of foot traction has been recognized as a major source of injuries in the workplace. In one analysis conducted in a large manufacturing facility in Great Britain, the incidence of foot slip-related injuries was 5.1 incidents per 100 man-years with a severity rate of 16 days restricted or lost per 100 workers.<sup>(1)</sup> The most serious consequences from loss of foot traction is a fall wherein the person strikes his or her head. Of the 69 000 fall-related injuries reported in Great Britain in 1979, about 3000 fatalities resulted.<sup>(2)</sup> More often the injury is a nonlife-threatening musculoskeletal strain injury, usually to the low back, ankle, or knee.<sup>(1)</sup> One U.S. airline reports 10% of acute injuries are caused by foot slips and twist or trip events common to fueling, baggage handling, and maintenance operations.<sup>(3)</sup> In Sweden, foot slips were reported to account for about 11% of all occupational injuries, of which 44% were on a level walking surface.<sup>(4)</sup> Construction workers, cleaning personnel, transportation workers, and restaurant serving personnel appear to be at particular risk.<sup>(5)</sup> These workers are often involved in tasks requiring moving of materials (e.g., pushing, pulling, and carrying objects) and are often walking on wet or contaminated surfaces. In the U.S., 17% of all disabling work injuries were attributed to falls (both from level walking and from heights).<sup>(6)</sup>

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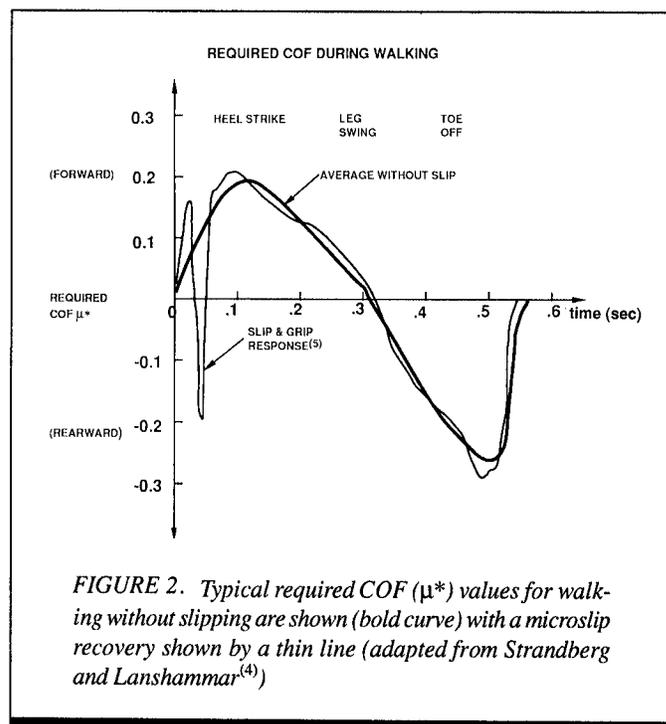
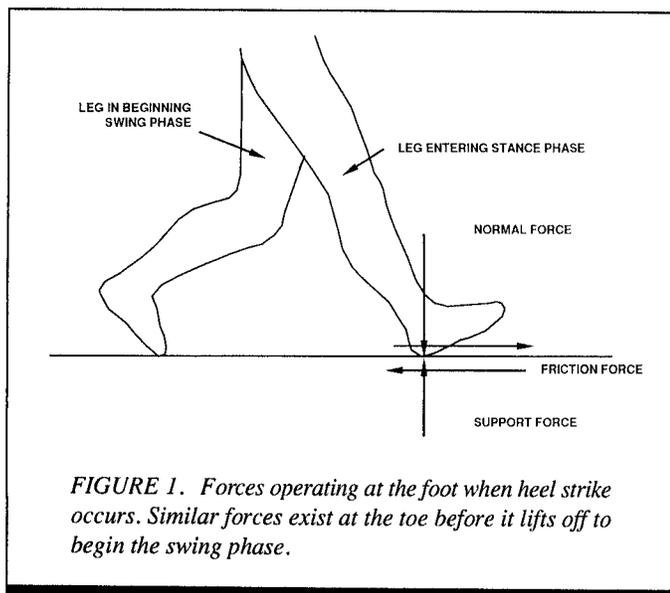
With more requirements that workers wear protective equipment, an increasing concern is being expressed regarding footwear in many work environments.<sup>(7)</sup> The U.S. Navy has recently developed boots that were meant to "provide a firm, non-slip grip."<sup>(8)</sup> Unfortunately, the resulting evaluation of the design did not include objective slip-resistance measurements, but rather emphasized fit and comfort. This is often the case with commercial footwear; hence, the protection provided against foot slip hazards is not known.

Arguments are often made that the best method of protecting workers against slipping and falling is training that results in slip-avoidance behavior. One study in the surface mining industry, however, disclosed that unsafe worker behavior was less important than the design of the equipment, e.g., walkways, ladders, and steps.<sup>(9)</sup> This concern has resulted in the recent proposed revision to OSHA regulation 29 CFR Part 1910—Walking and Working Surfaces—to include the following: "Stairs that may become wet or slippery as part of a work operation or as a result of weather conditions should be equipped with slip-resistant surfaces, such as non-slip finish or an abrasive paint."<sup>(10)</sup> Unfortunately, standardized and objective procedures for determining the degree of slip resistance were not included, perhaps because of the difficulty involved in determining the appropriate slip-resistance value, particularly in a workplace.

In this latter regard, many different research groups around the world have attempted to standardize slip-resistance measurement methods.<sup>(11)</sup> In all of the approaches it is assumed that the coefficient of friction (COF) developed between the shoe and a walking surface will represent the appropriate slip rating (and protective quality) of the shoe and floor. As simple as this appears, research continues to demonstrate that a variety of conditions must be considered when interpreting stated COF values. This paper discusses two major factors: the vertical (normal) load applied during shoe/floor contact and the speed at which the two surfaces are pulled across each other. Variations in shoe sole material, floor surface roughness, and the effect of water also are considered.

## THEORETICAL BACKGROUND

When walking, the first event to be considered in a single stride is when the heel comes down and contacts the walking surface (referred to as heel strike). It is at this phase of the stride cycle



that foot slip most often occurs, according to Strandberg.<sup>(5)</sup> The reason for this is that the ratio of the horizontal foot forces acting in shear when compared to the vertical foot forces is greatest in normal walking. These forces are shown in Figure 1. In this case, the horizontal foot force is referred to as the foot shear force and the vertical force is designated as the foot's normal force because the latter is perpendicular to the walking surface.

Also depicted in Figure 1 are the floor reaction forces. In this context, if the foot's shear force at contact is less than the friction force available, the foot will not slip because the two vertical forces are equal (i.e., the floor is stiff enough to hold the person's weight and downward inertia).

Another way to think of the system is to decouple the pair of orthogonal foot forces from the pair of floor forces. In this sense, a ratio of the foot's horizontal shear force divided by the foot's vertical normal force represents the COF required at the foot to stop the foot from slipping, or  $\mu^*$ . Clearly,  $\mu^*$  will vary, depending on several individual and task-related factors. During normal, level walking the  $\mu^*$  values shown in Figure 2 are typical. The absolute value normally will not exceed about 0.25.<sup>(5)</sup> If walking is more rapid than normal speed, however, the values increase to about 0.40. If pushing or pulling a heavy cart,  $\mu^*$  values can exceed 1.0, depending on the hand force required to move the cart.<sup>(12)</sup>

An interesting aspect of walking on slippery surfaces is also depicted in Figure 2. Lanshammar and Strandberg<sup>(4)</sup> had subjects walk on surfaces that caused the heel to start to slip and then grip (i.e., a micro slip was documented). They propose that such micro slip-and-stick events are common and serve to warn us to change our walking behavior, i.e., slow down, shorten stride length, and co-contract muscles necessary to stop a foot slip from becoming a fall.<sup>(4)</sup>

To protect workers from foot slip injuries, various groups have proposed that minimum values be set for the ratio of the friction force developed during contact of a shoe and floor, divided by the normal force exerted under standardized test conditions. In other words, by standardizing the shoe and floor conditions, applying a normal load, and measuring the resulting frictional force, the COF ( $\mu$ ) could be estimated. The resulting  $\mu$

values then could be used to rate or rank order the general slipperiness of a particular shoe-floor system. In other words, these standardized  $\mu$  values could be used to establish the slip hazard level for a given shoe or floor.

Prior to the mid-1970s, values of  $\mu$  for safe walking conditions were proposed to be between 0.4 and 0.5.<sup>(13)</sup> However, the methods for determining the  $\mu$  value for a particular shoe or floor material were not standardized, and this remains the case today. The efficacy of setting a particular safety limit, therefore, remains problematic, though studies are certainly reducing some of the uncertainty in this matter. In particular, the following factors have been recognized as affecting  $\mu$  values during the last decade.

### Velocity of Contacting Surfaces

As discussed earlier, when the heel strikes the ground for an instant it is moving. Heel-floor closing velocities may exceed 50 to 100 cm/sec. Leather, rubber, and other synthetic shoe sole materials interact in a variety of ways with hard surfaces. If a shoe sample setting on a hard, smooth surface is loaded with a weight and then pulled, the resulting value,  $\mu$  (i.e., the ratio of horizontal pull force divided by vertical force), will look like Figure 3 for most materials. The peak  $\mu$  value before the weighted shoe moves represents the static value of  $\mu$  (i.e.,  $\mu_s$ ).

As shown,  $\mu_s$  is often larger in magnitude than  $\mu_d$ , the dynamic COF measured when the weighted shoe is moving at a constant velocity. If this was always the case, then the measurement of  $\mu_s$  would not be as important in determining the slip hazard as  $\mu_d$ . Unfortunately, under some combinations of shoe/floor materials, contaminants, and surface geometries, the static and dynamic  $\mu$  values change drastically. For instance, James<sup>(14)</sup> showed that natural rubber (NR) on a smooth steel plate responds entirely different when wet compared to dry

conditions, as shown in Figure 4. Under very slow conditions (<1.0 cm/min), the values are almost equal. As the velocity increases into a range commonly documented at heel strike during normal walking, the wet surfaces exhibit a much lower COF. For this latter combination, knowing the static COF values would not help in rating the slip hazard. For this reason, most authorities recommend testing materials under both static and dynamic conditions.<sup>(15,16)</sup>

### Normal Loads on Contacting Surfaces

Although the basic assumption in computing the COF is that the friction force increases proportionally to the normal force holding the contacting surfaces together, under some circumstances this may not be true. One way to characterize the process that creates frictional force is to decompose it into two separate but additive components.

$$\text{Friction Force} = F_{\text{adhesion}} + F_{\text{deformation}}$$

As stated by Tisserand,<sup>(17)</sup> adhesion is most affected by lubrication, which lowers the COF, particularly during motion when the lubricant can best work between the two surfaces. Adhesion also depends on the time the two materials are in contact, particularly with wet leather.<sup>(18)</sup> Contact time appears to increase the static COF (a sticking effect caused by adhesion takes place), although under most walking conditions this is not believed to be a major effect because the floor-shoe contact times are very small, compared to when a person stands in one place for several minutes.<sup>(19)</sup> Deformation of the contacting materials is most affected by the stiffness of the materials, contact areas (i.e., roughness and size), and normal loads applied. Deformation forces are the reason that floor surface roughness measures have been found to correlate with dynamic COF values.<sup>(20)</sup> The rougher the floor, the higher the COF. Heel size would be expected to affect deformation forces, but because the actual heel contact area is small (i.e., back corner of the heel) at the time during the stride when high shear forces exist, the heel size (unless extremely small) is not a major problem.

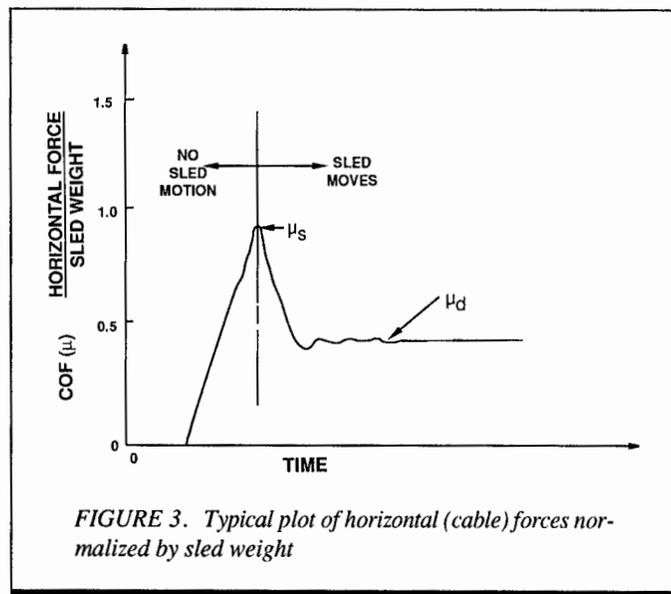


FIGURE 3. Typical plot of horizontal (cable) forces normalized by sled weight

The effect of the normal load magnitude is not simple to predict. When a soft material such as crepe is loaded heavily on a rough surface, the deformation force effect on friction will be larger than when using a smooth surface or harder shoe material. In other words, an interaction exists that complicates generalities about COF under light and heavy loads. This is particularly troublesome because some COF testing procedures use very light normal loads (less than 10 N), but others advocate quite high loads (1000 N). The light load testing devices may be used in the field, but the heavier loading devices most often are for the laboratory.

### The Effect of Contaminants

Any fluid contaminant between two sliding surfaces will provide lubrication and thereby lower the COF dynamic values. In essence, the fluid will behave as a hydrodynamic squeeze film, as discussed by Proctor and Coleman.<sup>(21)</sup> In this context, lubricating qualities are dependent on the following conditions.

1. Area of the contacting surfaces. The larger the area, the lower the dynamic COF values because the lubricant is not easily squeezed out.
2. Roughness of surfaces. The size, shape, and number of surface irregularities can allow the fluid to drain effectively, and hence improve dynamic COF values, compared to a smooth surface.
3. Velocity of the surface motions. Higher velocities will tend to trap fluids, but very slow velocities will allow time for fluids to drain.
4. Vertical loads. The greater the compressive forces acting on the fluid, the greater the amount of fluid squeezed from between the surfaces.
5. Fluid viscosity. The higher the viscosity, the longer the time required for the fluid to drain from between the surfaces.

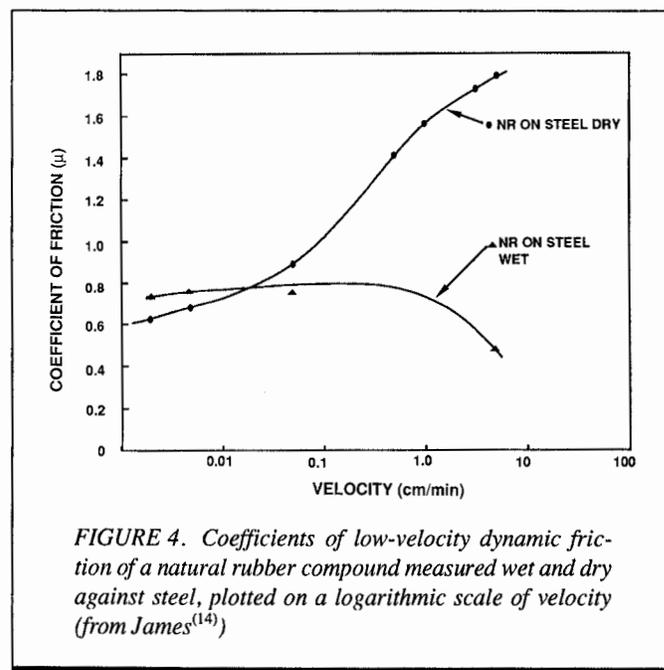


FIGURE 4. Coefficients of low-velocity dynamic friction of a natural rubber compound measured wet and dry against steel, plotted on a logarithmic scale of velocity (from James<sup>(14)</sup>)

## CONDITIONS TO BE TESTED

Clearly, a variety of factors affect both the static and dynamic COF values. Also, under dry conditions the static (or very slow speed) COF values are probably most representative of the hazard level, but under wet conditions the dynamic COF values become more relevant. On the basis of this background, a large set of tests was performed to evaluate the following, more typical, conditions for potential effects (and interaction effects) on both the static and dynamic COF values.

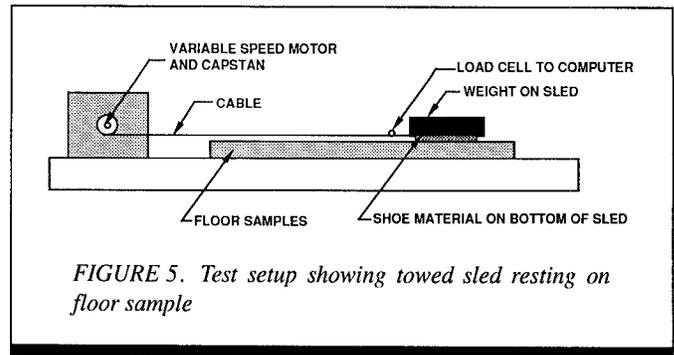
1. Vertical load (mass). 4.8 kg (10.6 lb), 11.5 kg (25.3 lb), 23.3 kg (51.3 lb), 35.1 kg (77.4 lb), and 47.8 kg (105.3 lb).
2. Velocity of motion (1, 5, and 10 cm/sec)
3. Shoe material. Soft crepe (Bernal hardness number [BHN] 67), leather (BHN 220), and hard Neolite™ (BHN 462).
4. Dry and wet contaminants
5. Surface roughness. Smooth glossy paint and rough paint (incorporating coarse sand with an average diameter of 0.8 mm and density of 28 grit per cm<sup>2</sup>).

## EXPERIMENTAL FACILITY AND PROCEDURE

The experimental facility was created to allow an accurate measurement of the dynamic force required to pull a weighted sled over the surface of the floor coverings of concern. The bottom of the towed sled was covered with 10 cm × 10 cm squares of the three different shoe materials similar to the Bigfoot COF testing device commonly used in industry. Figure 5 illustrates the test setup.

The experimental procedure was as follows.

1. Calibrate electronic load cell by using known weights.
2. Prepare floor material of masonite panels (60 cm × 60 cm) by sanding and painting with oil-based, high-gloss paint (normally two coats with no obvious brush marks for a smooth surface, or add 12 oz of coarse sand per gallon to second coat to create rough surface).
3. Prepare sled by taping 10 cm × 10 cm square samples of shoe material to the bottom, after lightly sanding samples to remove sheen.
4. Attach sled to computer-controlled stepper motor through load cell on sled.
5. Place appropriate lead bricks onto the sled to create desired vertical loads.
6. Add enough water to the surface of sample floor material to create a puddle under and around the sled for the "wet" trials.
7. Activate stepper motor at preset velocity and record horizontal force from load cell by using A-to-D signal sampling at 25 Hz. Display force graph over a 3-sec time period to ensure consistent data.
8. Repeat trials 10 times for each condition.



## EXPERIMENTAL DESIGN AND ANALYSIS

The static and dynamic COF values were computed for each trial by dividing the vertical loads into the peak horizontal "break-away" force and the mean of the horizontal forces while the sled was moving (see Figure 3). Because the experimental conditions were randomized in a factorial design, an analysis of variance was performed on both of the resulting COF values to determine significant differences with each experimental condition and the interactions. Each significant effect (including major interactions) was then ranked in accordance with the percent variance accounted for by each condition.

Last, because there is continued general interest in how static and dynamic COF values might correlate, a regression analysis of all the data was performed to compare the two types of data.

## RESULTS

Because the sample size is large (10 repeated trials for each of the 60 experimental conditions), all of the main effects, as well as the two- and three-way interaction effects, were significant ( $p \leq 0.05$ ). The resulting mean and standard deviations of the COF values for the three shoe materials tested under wet and dry conditions for smooth and rough floors are shown in Table I.

The analysis of variance ranking results are shown in Table II. Inspection of both the mean values and the analysis of variance rankings of significant effects provides insight into the magnitude of the effects on each condition of interest. Some general results are as follows.

1. The most consistently significant effect on both the static and dynamic COF values is the roughness of the walking surface (though hard Neolite was greatly affected by

TABLE I. COF Mean and SD Values for Major Test Conditions

	Smooth		Rough	
	Dry	Wet	Dry	Wet
<i>Static COF Values</i>				
Neolite™ (hard)	0.84 (0.26)	0.68 (0.16)	1.11 (0.13)	1.08 (0.20)
Leather (med.)	0.58 (0.15)	0.57 (0.23)	0.71 (0.14)	1.32 (0.31)
Crepe (soft)	1.09 (0.12)	1.01 (0.11)	1.55 (0.14)	1.51 (0.28)
<i>Dynamic COF Values</i>				
Neolite (hard)	0.66 (0.18)	0.36 (0.15)	0.67 (0.06)	0.55 (0.06)
Leather (med.)	0.37 (0.07)	0.29 (0.18)	0.46 (0.04)	0.74 (0.10)
Crepe (soft)	0.84 (0.08)	0.84 (0.15)	1.17 (0.08)	0.96 (0.12)

wetness). Walking on rough surfaces generally increased the mean static COF from 0.79 to 1.21 and the dynamic COF from 0.56 to 0.75.

2. Wetness reduced the dynamic COF for the hard Neolite shoe material from 0.66 to 0.36 on the smooth walking surfaces. Wetness also decreased the dynamic COFs for leather material on smooth surfaces, but had an opposite effect on the rough surfaces. The leather softened when wet, thus acting more like the softer crepe materials. This allowed more contact between the surfaces while decreasing the hydrodynamic lubricating effects.
3. Overall, the leather material resulted in the lowest COF values on the smooth surfaces with crepe consistently the best both on smooth and rough surfaces.
4. The effect of applied normal forces was greatest on wet leather, wherein the lighter test loads of 4.8 kg tended to result in increased COF values on smooth surfaces compared to the heavier loads used in the tests (Figure 6).
5. The velocity effect was not that important (<2% of variance affected) for the dynamic COF values. Velocity was

a more important effect for the static COF values, accounting for between 10% and 22% of the variance in the values. This latter effect was partially attributed to the sled's startup inertia. With higher velocities, the cable used to pull the sled would apply a larger impulse force to the sled, resulting in consistently higher peak static COF values before the sled began to move. This is a particular problem of all pulled-sled test devices, particularly when heavier loads are used.

A simple linear regression of all of the data provides a general relationship between the static and dynamic COF values across all conditions. This regression is shown in Figure 7. The results indicate that, on average, the dynamic COF values are approximately two-thirds the magnitude of the static COF values.

## CONCLUSIONS

Several practical conclusions become apparent from a review of the literature and the data presented in this study.

1. Dynamic COF values are potentially low enough to pose a significant slip hazard when smooth surfaces are walked on while wearing shoes with leather heels and soles, particularly if the surface is wet. Hard Neolite when wet also results in dynamic COF values low enough to be considered hazardous.
2. Softer crepe material appears to offer consistently high COF values. Such softer shoe materials may also provide additional protection to the lower extremities and lower back from the cumulative trauma associated with standing and walking on hard surfaces.<sup>(22,23)</sup>
3. The use of roughened walking surfaces has a beneficial effect in raising the COF values significantly under both dry and wet conditions. The effect of working on such high-traction surfaces wherein workers must continually rotate their feet is problematic, however. If the shoe cannot be easily rotated in such tasks, then additional torsional stress is placed on the knees and lower back. This "trade-off" deserves further study.

From a measurement perspective, it is clear that light load testing of floor surfaces may result in erroneous COF estimates under certain conditions (e.g.,

**TABLE II. Rankings of the Effect of Each Condition and Interactions Based on Percent Variance Explained by Each**

Source	Crepe		Leather		Neolite™	
	%	Rank	%	Rank	%	Rank
<i>Static COF Values</i>						
B <sup>A</sup>	67	1	44	1	42	1
C <sup>B</sup>	1	9	20	2	3	7
N <sup>C</sup>	4	4	10	3	4	5
V <sup>D</sup>	10	2	10	4	22	2
B, N	4	5	<1	12	5	4
C, N	4	3	2	7	4	6
C, V	<1	12	<1	13	1	11
N, V	3	6	6	5	3	8
B, C, N	<1	13	4	11	11	3
B, N, V	1	8	1	9	1	10
C, N, V	1	10	1	10	<1	12
B, C, N, V	1	11	1	8	2	9
<i>Dynamic COF Values</i>						
B	44	1	58	1	11	3
C	11	4	8	3	46	1
N	11	3	15	2	5	5
V	2	7	<1	12	<1	13
B, N	5	5	1	8	3	9
B, V	<1	13	<1	13	5	4
C, N	13	2	5	5	15	2
C, V	<1	11	4	6	1	11
N, V	<1	12	1	7	2	10
B, C, V	3	6	6	4	1	12
B, N, V	2	9	1	9	3	8
C, N, V	2	8	1	10	3	7
B, C, N, V	1	10	1	11	4	6

<sup>A</sup>Rough or smooth board surface.

<sup>B</sup>Wet or dry condition.

<sup>C</sup>Normal load on sled (4, 8, 11.5, 23.3, 35.1, and 47.8 kg).

<sup>D</sup>Towing velocity (1, 5, and 10 cm/sec).

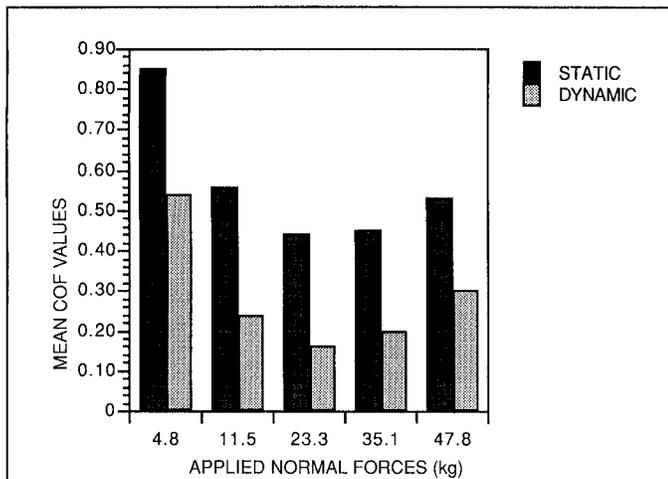


FIGURE 6. Effect of normal forces used during the testing of wet leather shoe material on a smooth surface

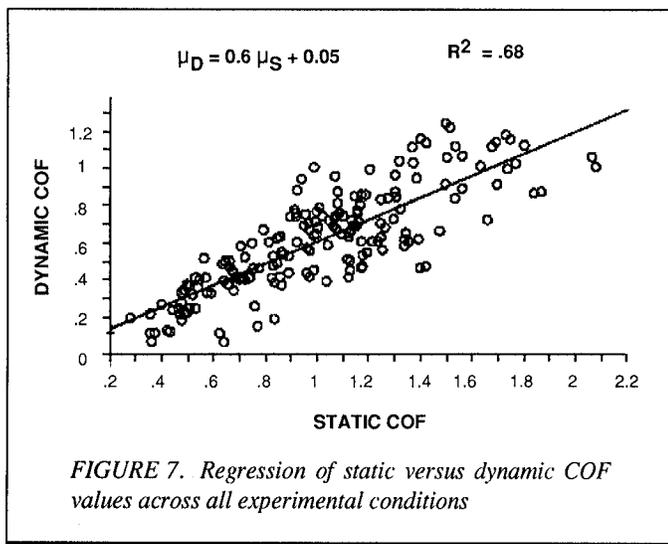


FIGURE 7. Regression of static versus dynamic COF values across all experimental conditions

wet leather).<sup>(24)</sup> The vertical loading range of 40 to 70 kg recommended by Tisserand<sup>(17)</sup> may be on the high side, however, on the basis of the results of this study. In general, this finding simply emphasizes the need for care in interpreting low vertical load test results and indicates the need to consider the hardness of materials being tested.

Similarly, static COF values will greatly overestimate the safety of floors under most conditions. Tisserand<sup>(17)</sup> has recommended dynamic testing be done above 20 cm/sec. The lower velocity data in this study indicate a very small effect on the dynamic COF values from 1 to 10 cm/sec, leading to the conclusion that under most conditions, dynamic testing could be accomplished at lower velocities than 20 cm/sec. When testing under wet conditions with smooth contacting surfaces, however, the higher velocity tests probably are warranted to make sure the hydrodynamic squeeze film effect is considered.<sup>(21)</sup>

A working group within the International Standards Organization standardization committee on foot protection was formed in 1983. A number of different tests have been compared for reliability and validity. Validity requires that the COF values

determined by specific tests be correlated with results obtained when people slip while walking on inclined surfaces or at varying speeds.<sup>(25)</sup> As yet, no standardized test has been developed for all shoe, floor, and contaminant conditions common to industry.

In summary, this paper is not meant to resolve all of the complex problems now apparent when measuring the COF of various shoe and floor surfaces, but it provides some further insight and guidance as to which experimental conditions are most important in making such measurements. In addition, the results clearly indicate the benefits of ensuring that walking surfaces are kept dry with a reasonable degree of surface roughness. Requiring shoes with a soft heel and sole material that also have drainage channels to reduce the effects of fluid film lubrication is certainly warranted in the many working areas wherein high COF values would be required.

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### ***American Industrial Hygiene Association Journal*** **Policy Regarding Products Mentioned in Technical Articles**

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