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The Effect of Contact Pressure and Test-Foot Sliding on Slip Resistance: Experimental Results

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ABSTRACT: Since the inception of interest in friction, the effect, if any, of contact pressure has been investigated. DaVinci, Amontons, and Coulomb, three early investigators, found no effect. The development of interest in walkway safety tribometry, the measurement of friction at the shoe-bottom/walking-surface interface, suggests a reassessment of the applicability of Amontons-Coulomb because the shoe bottom is resilient and because the interface between the shoe bottom and the walkway surface is frequently contaminated, for example, with a liquid such as water. In any such reassessment, the relationship between contact pressure and the friction coefficient becomes worthy of attention. Contact pressures in normal walking can vary upwards from a few psi to over a thousand psi (heelstrike in high-heeled shoes).

This paper will explore the historical background and experimental research in the literature and present the results of our experiments which explore the relationships between contact pressure and friction. The effect on friction of test-foot sliding is experimentally analyzed.

The relationship between the tribological results presented here and real-world walkway safety are discussed. The effect of test-foot polishing is analyzed. Future areas of investigation are discussed.

KEYWORDS: forensic science, tribometry, walkway safety, coefficient of friction, contact pressure, test-foot sliding, test-foot polishing

Classical, Amontons-Coulomb friction, a centuries-old theory, hypothesizes that friction is independent of contact pressure, standing time, and velocity. Amontons (1) attempted to measure friction by measuring the normal and lateral forces directly, and calculating the friction coefficient by dividing them. Coulomb (2) developed the first well-known, systematic compilation of friction coefficient values. Note that while neither Amontons nor Coulomb separated friction as to static or dynamic, the classical friction model named after them often incorporates that conceptual bifurcation. Amontons-Coulomb reasonably holds when the contacting materials are nonresilient; that is not necessarily the case in walkway friction, which can involve resilient bodies in contact.

Bowden and Leben (3) explored the dynamic friction between similar or dissimilar "clean" metals. Using a tester designed to eliminate dynamic effects, they found stick-slip occurring: violent for dissimilar metals and more subdued and regular for similar. They also found signs of localized welding and tearing of the surface implying that sliding involves material below the surface, even when the surfaces are lubricated. Temperature measurements showed a wild fluctuation of surface temperature during sliding with a sudden temperature "flash" at the instant of slip. The exact behavior depends upon the relative physical properties of the metals, particularly on the melting point, and there is evidence that three distinct types of sliding may occur, relating to three distinct types of metallic junctions. They wrote that the detailed analysis of the frictional force shows that the classical laws of friction can be regarded only as crude approximations.

Bowden and Tabor (4) discussed the forces occurring at the microscopic level with and without contamination at the interface. The adhesive forces at the junction of the asperities, they wrote, are very strong, but the normal adhesion between surfaces that have been pressed together is usually very small. This is due mainly to the effect of released elastic stresses or other types of stress concentration that rupture the junctions as the joining load is removed. The authors thus suggest that frictional measurements may provide more information about the nature of surface adhesion than the direct measurement of adhesion itself. In some cases, liquid films produce strong adhesive forces between solid surfaces, but these are essentially a result of surface tension and viscous forces. On the other hand, contaminant films that separate the surfaces by more than a few angstroms can produce a profound reduction in the adhesion. At the limit, if the surface film completely prevents solid-solid interaction, the adhesive strength at the interface is primarily determined by the strength of the contaminant film itself.

Conant and Liska (5) extend the work of Bowden and Tabor to rubber and rubber-like materials. They write that at the pressures and velocities likely to occur in normal walking, Amontons-Coulomb is likely to hold reasonably true. This comprehensive paper includes an extensive, 165-item bibliography.

Grosch (6) explored the relation between friction and viscoelastic properties of rubber. The author writes that it is clear that friction of rubber on hard surfaces is due to two causes: (1) the adhesion of rubber to the surface and (2) the deformation occurring in the rubber when it slides on rough surfaces. Sliding several rubbers of widely differing viscoelastic properties on smooth and rough surfaces over a wide range of temperatures and sliding velocities, Grosch found that curves giving coefficient of friction as a function of the sliding velocity at different temperatures are segments of a single "master curve" that describes the coefficient of friction over an extended range of sliding velocities at a selected reference temperature.

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Bowden and Tabor's (7) monumental treatment of the subject of friction contains a particularly complete history. They trace the history of the understanding of friction, starting with the Egyptians, as early as 1900 BC, and extending up to modern times. Most of the material is on friction between two metallic surfaces, with particular emphasis on the effects of lubricants. There is material on the friction of wood and of lubricated rubber, but there is very little data relating directly to shoe and flooring surfaces.

Ludema and Tabor (8) explore the friction and viscoelastic properties of polymeric solids in an attempt to link the frictional properties of polymers with their viscoelastic characteristics. They measured friction over wide speed and temperature ranges, showing that, for rubber, there is a close relation between the sliding friction at various speeds and temperatures and its viscoelastic properties. They hypothesize a very simple model in terms of the way in which the area of contact and the interfacial shear strength vary with rate of deformation and temperature. Rolling friction, the authors wrote, correlates very well with conventional viscoelastic data. Presumably with rubber, slip-of-chain segments over one another remain the basic mechanism of shear even at the high strains involved in sliding.

Moore's (9) historical survey of surface texture effects ranges from pipe flow roughness factors to molecular roughness concepts. Techniques for measuring surface features are classified according to whether the scale of roughness lies in the macro or micro regimes. Moore believes that at least five parameters are in general required to specify uniquely and completely surface features. The effects of texture design on adhesion, hysteresis, lubrication, and squeeze films are given, and the subject of macroelastohydrodynamics receives special emphasis. Moore indicates that friction is intimately related to the surface texture of the two surfaces and to how they are affected by any intervening foreign material, such as a lubricant. Most of the work to date has been confined to pairs of rigid surfaces, such as metals, but resilient surfaces, such as leather, rubber, linoleum, and so forth are also of interest where the surface is likely to deform under the normal pressures present. He goes on to discuss some of the techniques that have been used to evaluate the surface character of a variety of materials, demonstrating that there is much yet to be learned about surface features and that the learning will require considerable experimental effort. This paper has an extensive, 83-item bibliography.

Drutowski (10) researched the motion of a hard sphere against a flat elastomer both analytically and experimentally. He used a transparent spherical indenter enabling continuous measurement of contact size while the samples were pulled apart. For any combination of load and contact area, the author found separate regions: a circular zone under compression and an outer annulus under tension.

Schallmach (11) discusses an underlying mechanism for rubber materials sliding. Visual observations of contact areas between soft rubber sliders and hard tracks and between hard sliders and soft rubber tracks show that relative motion between the two frictional members is often only due to "waves of detachment" crossing the contact area at high speed from front to rear. Adhesion appears to be complete between these waves, which are moving folds in the rubber surface, almost certainly produced by buckling, attributed to tangential compressive stresses.

Roberts (12) outlines the development of dry-rubber friction theory. Roberts and Jackson (13) report experiments that demonstrate that it is possible to predict quantitatively the level of sliding friction of rubber arising when a smooth rubber sphere slides on glass. Analysis of the sliding friction is based on a surface energy approach. Observations show that when a smooth rubber surface advances over glass, by a continuous peel process (Schallmach Waves), the work done in the region of contact can be calculated in terms of a rate-dependent surface energy, and thus an expression found for the tangential stress required to maintain uniform relative motion between the surfaces.

Roberts and Thomas (14) study the adhesion and friction of smooth rubber surfaces via an optical study of contact-area-time effects and show in a simple way how optical observations may be used to predict the rate of rolling of a ball bearing on smooth rubber, the time taken to detach itself under gravity, and its resilience when bouncing on smooth rubber. The friction when a rigid surface slides over smooth rubber under conditions in which Schallmach waves are generated is also shown to be quantitatively related to their mutual adhesion.

Kendall (15) studied rolling friction and adhesion between smooth solids. The contact between a smooth cylinder and a flat surface can be regarded as an adhesive junction bounded by two cracks moving in the same direction at the same speed, one crack continually opening and one closing. Propagation of these cracks requires a force that is calculated from crack theory and shown to be equal to the friction. The theory has been verified experimentally using glass cylinders rolling on smooth rubber. Moreover, this adhesion interpretation of rolling friction between smooth surfaces explains several observations: (1) the existence of a static rolling friction, the unusually high value of friction, and its independence from load and roller radius and (2) the marked effect of lubricant or dust.

Klamecki (16) promulgates a catastrophe theory description of stick-slip motion in sliding by studying structural changes in the mathematical model describing sliding friction. The sliding system is assumed to operate in a way that minimizes energy input to the system.

Fritzon (17) explored the friction of elastomer composites sliding on cast iron as a function of surface temperature, sliding speed, and pressure. The author found that the friction coefficient is highly dependent on the surface structure, which is in a state of continuous change during the test. This phenomenon is the cause of greatest variation in the friction coefficient. Increasing temperatures result in lower friction coefficients with weak or no significant dependence on pressure and sliding velocity.

Sigler et al. (18) studied the effect of contact pressure on test results obtained using the pendulum tribometer that Sigler developed while at the National Bureau of Standards. The authors found that varying the contact pressure between 40 and 120 psi (276 to 827 kPa) produced significant differences in results, especially under dry conditions. Specifically, higher pressures gave lower friction coefficients, but the relative slip-resistance ranking of different walkway surfaces did not shift under varying pressure.

Weirich (19) used the James tribometer with steel test feet and test surfaces, and then with leather test foot on an asphalt test surface, both waxed and unwaxed, to investigate the effect of contact pressure on static friction.

Irvine (20) used a motorized drag-sled tribometer to test at pressures ranging between 6.1 and 18.3 psi (42 and 126 kPa) with a number of test foot and test surfaces under dry and wet conditions to explore the effect of contact pressure on slip resistance.

Experimental Procedure

The objective of the contact-pressure experiments was to explore the relationship between available friction and contact pressure in the tribometric-test pressure regime under ordinary temperature and humidity conditions. Test-foot materials included two shoe-bottom surrogates: Federal standard leather (as used in the ASTM Test Method for Static Coefficient of Friction of Polish-Coated Floor Surfaces as Measured by the James Machine D 2047). Neolite® test liner (as used in the ASTM Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynanometer Pull-Meter Method (C 1028), and one common shoe outsole material (Bilt-Rite 882, "Crinkle" finish outsole). White, glazed bisque tile, red, unglazed quarry tile, and vinyl composition tile, all used both as tribometric test surfaces and floor surfaces, were used in the experiments.

Two distinctly different walkway-safety tribometers were used for the experiments: a Portable Articulated Strut Tribometer (PAST),[3] a device loosely modeled on the James Tribometer, and the Portable Inclined Articulated strut tribometer (PIAST),[4] an instrument specifically designed for wet-surface tribometric testing. The latter tribometer is by design capable of giving meaningful wet-test results because the in-plane and normal forces are applied simultaneously, generating hydrodynamic effects that, to some degree, mimic a wet-surface pedestrian slip.

The contact pressure of the 3-in.^{2} (4.6-cm^2) test foot was varied by reducing the width of the test-foot material; this method was chosen to avoid the possibility of anomalous mechanical interlock.[5] The experiments were limited to contact pressures in the range typical of tribometric tests. Given the 12-lb (5.4-kg) surcharge, it would not be feasible to test the higher end of the heelstrike-pressure envelope; the test-foot material would have been of such small area that it would compromise the material's mechanical integrity.

The first experiment, using the PIAST (Slip Test Mark II), tested standard leather on the ceramic-tile test surfaces and explored the relationship between contact pressure and slip resistance. An experimental design was used having four replications in each of four orthogonal directions, for a $4 \times 4 \times 3 \times 2$ experimental design (4 replications $\times$ 4 directions $\times$ 3 contact pressures $\times$ 2 tiles).

The second experiment, again to explore contact pressure, used the PIAST, testing a common shoe outsole material (Bilt-Rite 882 "crinkle" finish) against vinyl composition tile under wet and dry in a $6 \times 5 \times 2$ experimental design (6 replications $\times$ 5 pressures $\times$ 2 conditions [wet, dry]). The wet condition was accomplished by spraying tap water on the test surface; the water was refreshed frequently to assure that there was a continuous film.

In the third experiment, which explored both contact pressure and the effect of test-foot sliding since test-foot reconditioning, the PAST (Slip Test Mark I) and standard-leather and Neolite-test-liner test feet were used on dry vinyl-composition, ceramic-quarry, and bisque-tile test surfaces. A $6 \times 4 \times 3 \times 2$ test design (6 replications $\times$ 4 contact pressures $\times$ 3 test surfaces $\times$ 2 test-foot materials) was used. The number of tests following reconditioning of the test foot was recorded along with the other data.

In the fourth experiment, designed to isolate the effect of test-foot sliding, the Slip Test PAST with standard leather and Neolite test liner on vinyl composition tile was used. In this experiment, a $2 \times 4 \times 4$ experimental design (2 test feet $\times$ 4 directions $\times$ 4 replications) was used. As in experiment 3, the number of tests since the test foot was reconditioned was recorded.

Results of the first three experiments were analyzed using the multivariate general linear hypothesis methodology (MGLH) in Systat (21), a desktop-computer statistical analysis program. MGLH allows one to test simultaneously the significance of categorical and quantitative factors. Ordinary least-squares regression (OLS) was used to analyze the data generated in the fourth experiment.

Results

In the first experiment, it was found that tile type and contact pressure were significant ($p = 0.000$ and 0.004, respectively.) It can be seen in Fig. 1 that the effect of contact pressure, while clearly statistically significant, was both slight and interacted with the tile type ($p = 0.000$). That implies that the relationship between pressure and friction is not simple. Directional effects were not significant, and the remainder of the contact pressure experiments assumed isotropy.

In the second experiment, real-world shoe-bottom outsole material was tested wet and dry at increasing contact pressures with Slip Test Mark II PIAST. It can be seen in Fig. 2 that the wet and dry curves are similar but displaced in level; the wet-surface friction was significantly less than the dry ($p < 0.001$). The effect of contact pressure was significant ($p = 0.001$) but relatively slight.

In the third experiment, standard leather and Neolite test liner were used against quarry and glazed ceramic tile and vinyl composition tile (see Fig. 3). The test-foot material, pressure, test order, and the interaction between test sequence order and pressure were all highly significant ($p \leq 0.001$). Remarkably, the test surface was found to be at best marginally significant ($p = 0.18$).[6] The strongest determinant of the slip resistance was found to be the test order, expressed by the test-sequence number, implying a change in the surface of the test foot, presumably as a result of the roughening or polishing effect of the test foot sliding on the

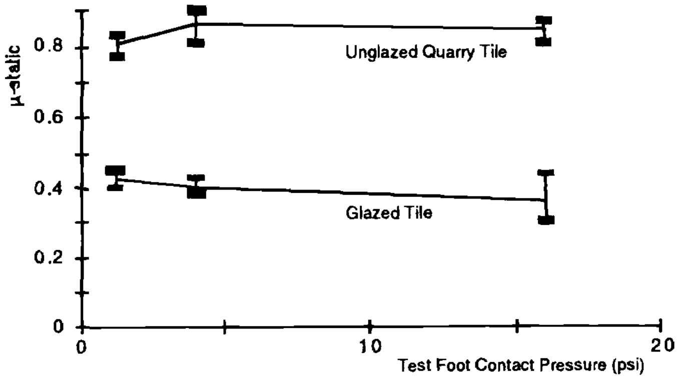

FIG. 1—*Static friction versus test-foot contact pressure. Tribometer: portable articulated inclined strut tribometer (Slip Test Mark II), test foot: standard leather—Dry, and test surface: ceramic tile.*

[3]Here, the Slip Test Mark I was used.

[4]Here, the Slip Test Mark II was used.

[5]Note that some drag-sled tribometers and the Tortus dynamic tribometer use one or more small circular test feet. The closest analog to human footwear would be a high or spike-heeled shoe heel, not at all typical of ordinary footwear. Such small test feet react to test-surface variations in a scale-variant manner vis à vis ordinary footwear or bare feet. Test surface dimensional variation seen in ordinary embossed resilient flooring, brick and concrete pavers, and wood and tile floors is of a magnitude that it can cause in conjunction with these tiny test feet mechanical interlock which can confound tribometric test results.

[6]Distinctly different test surfaces like the ones used in these experiments, should give rise to, in our opinion, statistically significantly different tribometric results. We hypothesize that the strength of the interactions relative to the test-surface factor caused the anomalously high p-value.

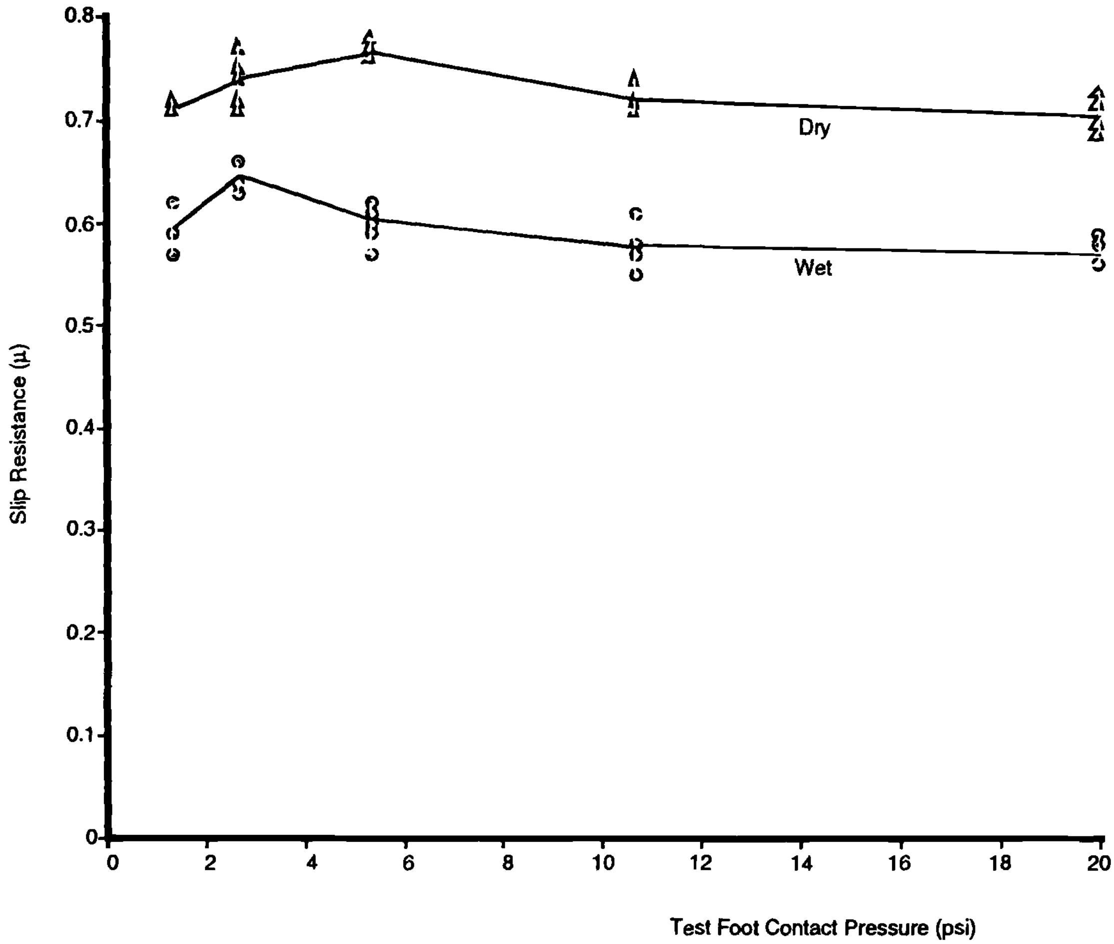

FIG. 2—*Slip resistance versus test-foot contact pressure with real-world outsole material. Tribometer: portable articulated inclined strut tribometer (Slip Test Mark II), test foot: Bilt-Rite 883, "crinkle" finish, and test surface: vinyl composition tile.*

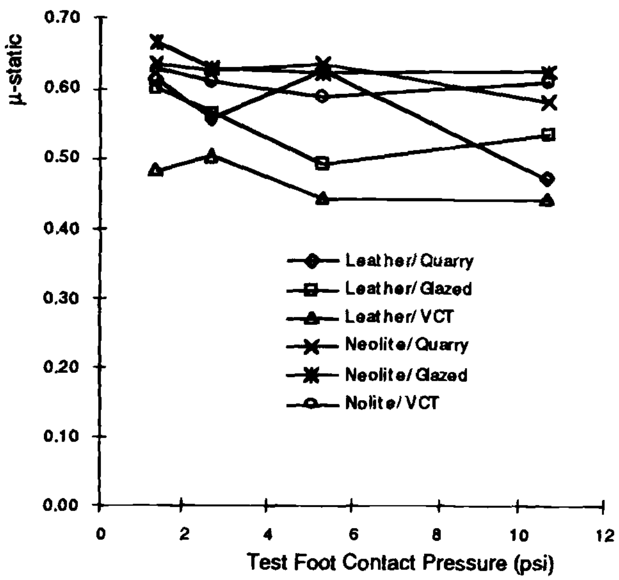

FIG. 3—*Static friction versus test-foot contact pressure with common tribometric test materials. Tribometer: portable articulated strut tribometer (Mark I), test feet: standard leather and Neolite test liner, and test surfaces: glazed tile, quarry tile, and vinyl composition tile.*

test surface. A sequence plot of the data (Fig. 4) sets reveals no obvious trend (the abscissa represents the test number; the ordinate, the static friction coefficient).

In the fourth experiment, to isolate the relationship of friction changes with test order, a Slip Test PAST with standard leather and Neolite test liner test feet was used against vinyl composition tile in a series of tests in which the test foot was used for 16 tests between test-foot reconditioning. Each set of 16 tests was repeated 4 times for both the leather and Neolite test feet. Each test caused the test foot to slide along the test surface a distance of approximately 0.05 in. (1.3 mm). The results obtained are seen in Fig. 5. All regression coefficients were significant ($p < 0.001$).

Discussion

Notwithstanding the statistical significance of contact pressure on friction, the slight slope of the friction/contact-pressure curves and the fact that slope was in one case positive, in another, negative, and in a third, positive changing to negative, suggest that the Amontons-Coulomb hypothesis that friction is independent of contact pressure appears to hold—at least roughly—for dry smooth surfaces and within the rather narrow pressure band that characterizes tribometric testing contact pressures. It would be inappropriate to extrapolate these results to human-subject gait analysis. Given their different operating characteristics, extrapolation to other tribometers could be equally problematic.

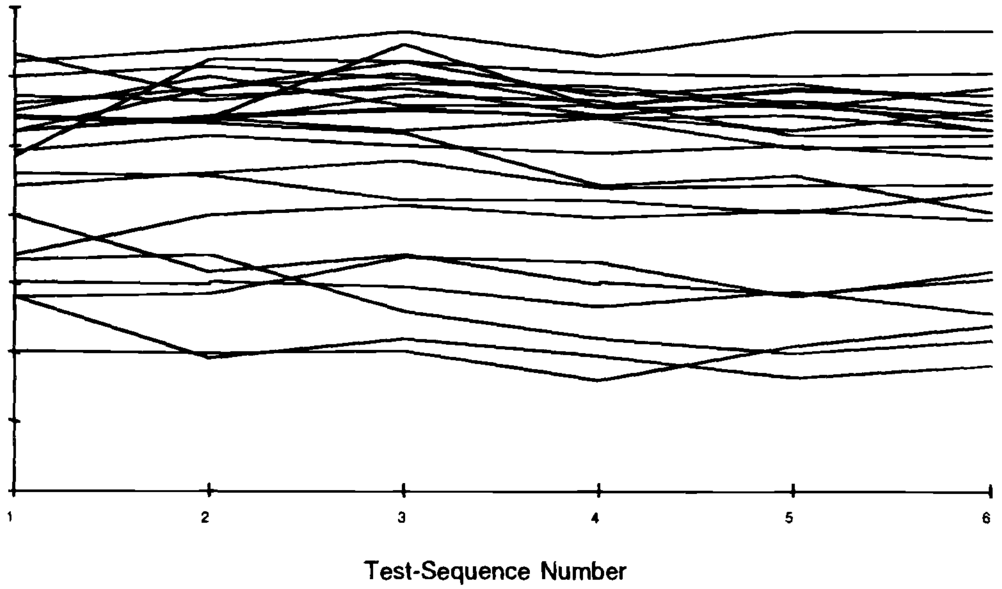

FIG. 4—*Sequence plot of static friction versus number of tests since test-foot conditioning. Test data replotted from Fig. 3.*

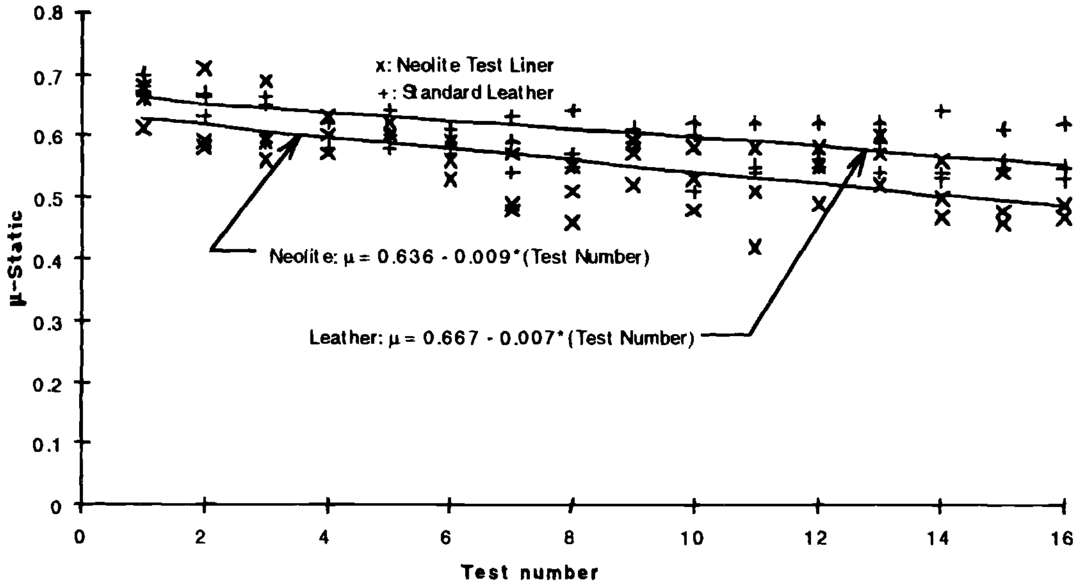

FIG. 5—*Static friction versus number of tests since test-foot conditioning. Each test number represents a test-foot travel of 0.05 in. (1.3 cm). Tribometer: portable articulated strut tribometer (Mark I), test foot: standard leather and Neolite test liner, and test surface: vinyl composition tile.*

Of significant import is the question of whether or not textured shoe-bottom material can prevent hydroplaning, which lowers the measured friction by at least an order of magnitude. In Experiment 2, with a single type of "crinkled"-texture shoe-bottom material, it was found that hydroplaning did not occur at tribometric contact pressures. The fact that we did not observe hydrodynamic effects suggests that in those situations in which footwear type and condition can be *strictly* controlled, for example, some employer/employee relationships, it should be possible to control slip propensity through footwear alone or through footwear and floor surface, rather than through the far more common amelioration strategy of controlling the floor surface alone.

The test-foot-sliding data extracted from Experiment 3 gave equivocal results in spite of the fact that the test-sequence-number factor—a surrogate for test-foot sliding distance—was highly significant. We believe that contact pressure variation confounded the test-sequence-number factor; the fact that the interaction between contact pressure and test sequence number was highly significant supports this inference.

In the fourth experiment, which isolates the effect of test sequence number, a significant relationship between test number and friction is shown. In the domain of the tests, the friction relationship was reasonably linear. It is clear, at least for the standard leather test foot and vinyl composition tile test surface that we used in the last experiment, that the effect of test-foot sliding is predictable. This has two implications. First, it should be possible to predict and correct any anomalies caused by improper test-foot-conditioning technique. Secondly, conditioning the foot by sanding is a time-consuming process. Given that, it might well be possible, at least when using a PAST, to skip conditioning the test foot, thus shortening considerably the time needed to conduct tribometric tests by later mathematically correcting the results.

This would be accomplished by recording, for each test taken, the number of tests performed since the test foot was last reconditioned: the *test sequence number.* Later, a regression analysis using the test sequence number as the independent variable and slip resistance as the dependent could generate regression coefficients that be would used in a straightforward manner to eliminate the effect of not reconditioning the test foot. In our experiment, the regression-predicted friction coefficients at Test Sequence Number 1 provides corrected estimates for the static-friction coefficients: 0.66 for standard leather and 0.63 for Neolite test liner. While the technique described here is generally applicable, the specifics: use of a linear model, the regression-coefficient estimates, and the corrected slip-resistance values, are specific to the experiment performed. Certainly, the use of these coefficients and estimates should not be extrapolated to other data or test conditions.

Directions for Future Research

An obvious extension of this experimental work would be to extend the pressure range into the regime encountered at heelstrike, in some cases, over 1000 psi (6890 kPa). A second obvious extension would be to test materials systematically used in footwear today, which includes both synthetic materials and different grades of leather tanned in different ways.

The issue of wet-surface slip resistance is one of the most important in pedestrian safety. Research is needed to determine the effect of outsole texture at heelstrike-level forces and to define wet-surface friction levels as a function of outsole material, outsole tread pattern, and outsole wear against different walkway and tribometric-test surfaces.

The issues of test-foot and test-surface preparation are significant. Voluntary consensus standard development in these two areas is presently underway in the ASTM Committee F-13 on Safety and Traction for Footwear Standardization of test-foot conditioning methods (typically, for leather or Neolite test liner, sanding with fine-grit abrasive paper) is desirable. The question of test-foot conditioning and its interaction with shoe-sole texture must be addressed if tribological tests using textured outsole materials are to be repeatable and meaningful. Finally, the issue of the shape of the friction versus the test-foot-sliding curve—well represented by a linear relationship for the range of test-foot-sliding distances explored—needs experimentation. The total test foot slide distance in our experiments using a PAST was (16)(0.05) = 0.8 in. (2 cm). The PIAST has a slide distance of over twice that each time it slips. It should be clear that a linear relationship cannot be sustained with increasing test numbers.[7] We speculate that the curve is likely exponential.

[7]The friction cannot linearly decrease indefinitely as it cannot become negative.

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