ON THE REDUCTION OF SLIP OF RUBBER CRUTCH-TIPS ON WET PAVEMENT, SNOW, AND ICE[a]

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STATEMENT OF THE PROBLEM

"Omnia e qualunque cosa per sottile ch'ella sia, la quale s'interposiga in mezo infra lle cose insieme confregate, allegrerisue la difficulta di tale confregazione."

"All things and everything whatsoever, however thin it be, which is interposed in the middle between objects that rub together, lighten the difficulty of this friction."

Thus did Leonardo da Vinci (1) (2) around the year 1500 make the accurate and general observation of that condition which governs also the specific problem facing the disabled who use walking aids on wet pavements, in snow and ice around the freezing point.

INTRODUCTION TO THE CLINICAL NEED

Many millions of disabled people rely on the aid of sticks, crutches, and other aids for walking. All these aids have rubber tips at their base. The main reasons for this tip are: to reduce slipping caused by contact between metal or wooden aids and the floor, quietness in use, replaceability of the tip when worn.

Such tips have not been the only method proposed for dealing with these problems; the literature shows (3) many hundreds of ingenious mechanisms for ensuring a complete grip on the floor by the stick. None of these has found mass use for the very reason that the solutions proposed are too ingenious and too complex for real life with its problems of economical supply, ease of maintenance, avoidance of damage to the floors, and reliability. Complexity and reliability are, in our real everyday lives, mutually incompatible; the disabled person needs a very high degree of reliability from his devices.

[a] The author has applied for a patent for the improved crutch-tip described herein.

So the rubber tip is a practical aid; but it does suffer from serious weakness, especially in wet weather, or in ice and snow, when the present standard tip tends to slip quite badly. Such tendencies tend to make the user alter his method of walking and to become less confident of his security.

The problem is one from which most disabled people have tended to suffer in silence, for one reason or another. Perhaps they have considered it too trivial to complain about. For whatever reason, the problem of designing non-slip rubber crutch-tips has certainly not been studied seriously. The literature shows no analysis of the problems of non-slip crutch-tips; no improvements have been made to the standard article for many years. Crutch-tips sell for between $.30 and $2.00 a pair; the problem is perhaps mundane, literally beneath the dignity of examination by scientists and engineers. But the deficiencies of tips cause anxiety and danger to millions and for this reason alone they must have some attention.

ELEMENTARY SCIENTIFIC CONCEPTS OF FRICTION BETWEEN SURFACES

In order to understand the nature of the contact between a rubber crutch-tip and the walking surfaces, it may be helpful to review current scientific knowledge of the nature of friction between solid surfaces.

The frictional behavior of sliding surfaces has been studied for a long time. In fact it was Leonardo da Vinci (4) who seems first to have reported the two basic laws, although his notebooks do not record any satisfactory, confirmatory experiments.

Dry friction is defined as the force between the surfaces resisting or opposing relative sliding motion or, in the static case, the *tendency* to slide.

First Law

The frictional force varies with the applied load.

Second Law

It is independent of the (apparent) area of the surface over which it is applied.

As we have already noted, Leonardo da Vinci also carefully observed that frictional force was reduced markedly by the interposition of a layer of slippery or greasy fluid, however thin, between the surfaces.

These laws were rediscovered by the French engineer Amontons (5) in 1699 and are named after him. His experimental confirmation was made with the use of a surprisingly advanced and yet elegantly simple method and apparatus (Fig. 1).

He realized that the touching surfaces were not flat and he asserted that the roughnesses must enter into each other. This speculation was, of course, correct, but Amontons then went on to assign the frictional

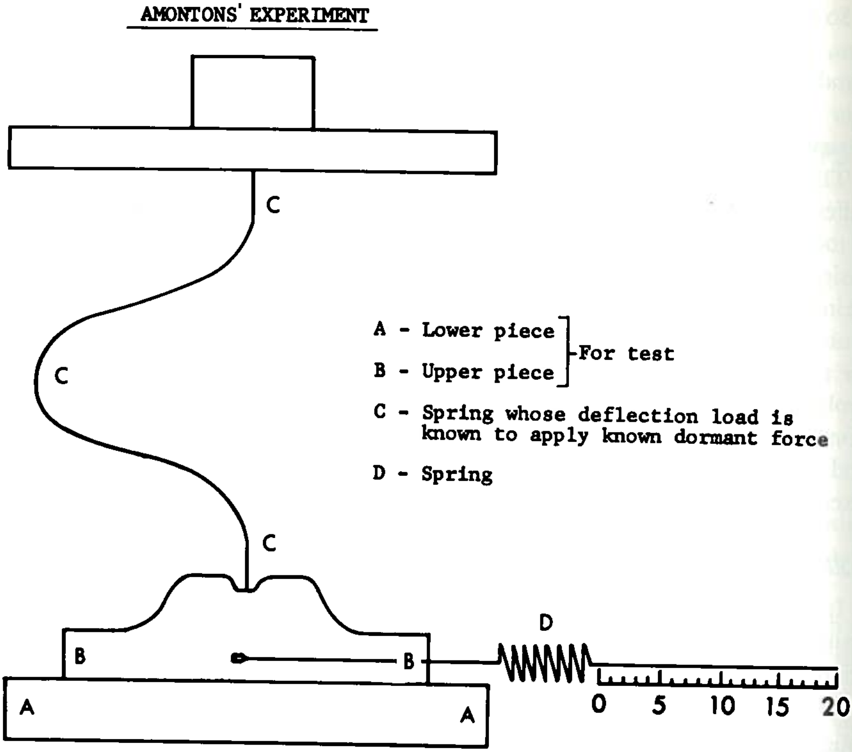

FIGURE 1

force to the effort of pulling the top plate over the asperities of the bottom one, as if up an inclined plane; whereas with our knowledge of the micro-structure of surfaces, we now know this not to be the case.

His observations were verified by Coulomb (6), in the 1780's, who made a distinction between static friction—the resistance and therefore the force needed to *start* sliding—and kinetic friction, the resistance and therefore the force required to *maintain* sliding motion. It will be immediately obvious that this distinction between types of friction is of great important in these discussions since the prevention of the onset of sliding motion is of importance. Coulomb showed that once in motion, the kinetic friction could be significantly lower than the static friction.

A combination of this observation and of Leonardo's of the effect of the interposition of a liquid or greasy layer yields the very low values of frictional force opposing the motion of the crutch-tip skidding on wet pavement.

These laws may, at first sight, be somewhat surprising. More recent scientific investigations, especially by Bowden and Tabor (7), have explained them by detailed theory and observations.

Their work related firstly to the true nature of contact between surfaces. As Amontons asserted, practical surfaces are not completely flat, and two surfaces contact one another only at the asperities. The true area of contact depends on the load and on the bulk properties of the materials because these determine how far the materials sink into each other, and also their resistance to fracture. Experiments show that the asperities are "welded" together during contact, and sheared during later motion. The true area of contact

$$A = \frac{\text{Applied load}}{\text{Yield stress of the softer material}} = \frac{W}{S}$$

If the frictional force is now defined as that force required to shear the junction formed between the asperities

$$F = A \times s, \text{ the mean shear stress}$$

and therefore

$$F = \frac{W\,s}{S}.$$

Thus we can see that the force depends only on the applied load and the bulk deformational properties of the materials.

We have now derived Amontons' First and Second Laws and combined them into one equation; but it only applies when the materials are in contact.

It clearly does not hold when the surfaces are separated by a lubricating layer, because this layer prevents the true area of contact from increasing with increasing load; the additional load being taken, largely, by distribution of the stress through the fluid layer. As we shall see, with very elastic materials such as rubber, there is, additionally, another source of frictional force which can be exploited to increase the friction.

SPECIAL NATURE OF THE FRICTIONAL BEHAVIOR OF RUBBER WITH A RELATIVELY INELASTIC SOLID

The previous discussion related implicitly to the case in which both surfaces were made of relatively inelastic materials. When one of these materials is very elastic, the nature of the forces at the surfaces changes. As before, we shall start by considering the departure from flatness of real surfaces. The materials will touch at their asperities and when one body is moved relative to the other the frictional force will now be made up of two components: one due to the adhesion forces between the materials, and the other due to deformation of the more elastic material.

Thus

$$F = F_{adh} + F_{def}.$$

F_{adh} can be expected to follow Amontons' Second Law and be independent of overall dimensions. The adhesion force can reach quite high

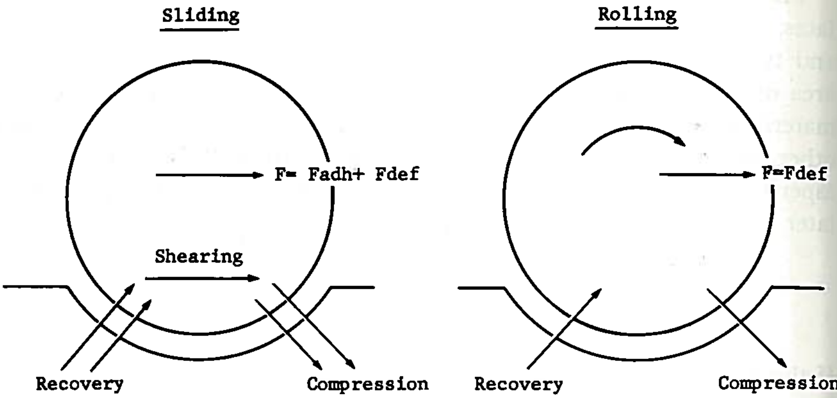

FIGURE 2.—From reference 9.

values in dry friction. In rubbers the force is very sensitive to the surface condition and to the thermodynamic properties of the rubber. A discussion of these is inappropriate in this paper; see Grosch (8) for a full treatment. The second term is very dependent on load and on the bulk properties of the material.

This hypothesis is confirmed by experiment. Bowden and Tabor (9), for example, report the results of comparing the frictional resistance of sliding and of rolling a steel ball over rubber sheets (Fig. 2).

In the second case, the friction is largely due to the deformation and hence to the hysteresis of the rubber (see below). The higher the hysteresis, the higher the friction (Fig. 3).

FRICTION OF WELL-LUBRICATED RUBBER AND A RELATIVELY INELASTIC SURFACE

When the two surfaces are separated by a lubricating layer the force due to adhesion is absent and the friction is due only to the viscosity of the fluid layer, which in our case is unfortunately low and can be neglected, and to the deformation of the rubber. Clearly the lubricant must be penetrated and the rubber must make contact with the pavement, promoting static friction. For this reason it is advantageous to break up the surface of the rubber body so that the fluid film can be pushed aside.

Careful design of the rubber surface pattern will also promote rolling friction as opposed to sliding friction. In rolling friction the deformation of the rubber provides the friction. The existence of rubber asperities penetrating through the fluid film and contacting the pavement will also enable the friction to be increased by the ability of rubber to store

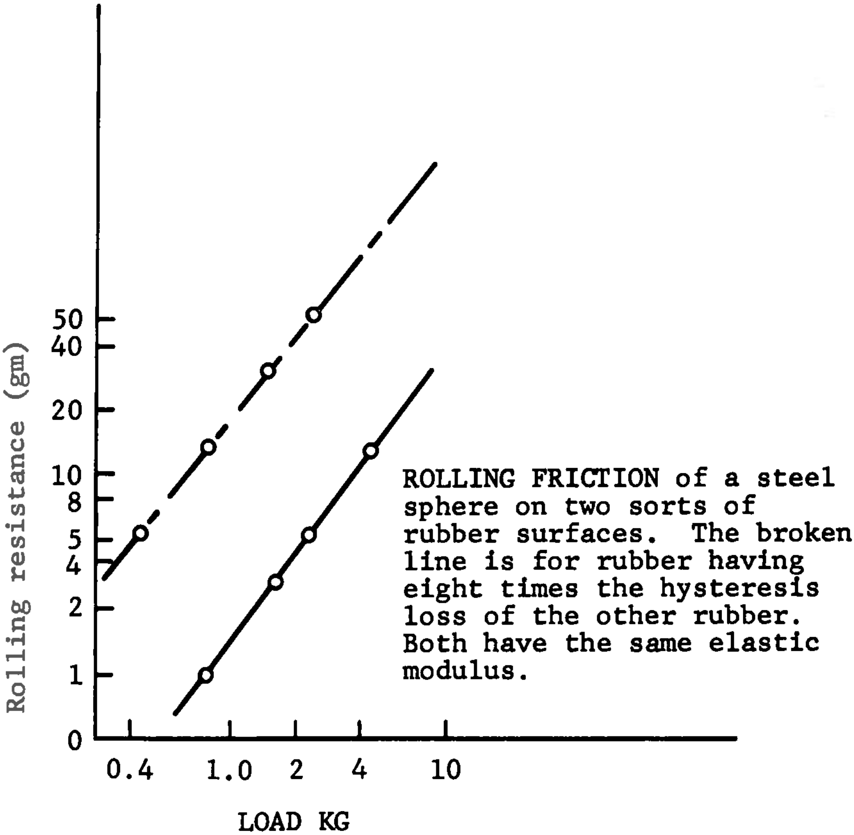

FIGURE 3.—From reference 9.

elastic energy; this property is called hysteresis. As with the case of dry friction, the higher the hysteresis the higher the friction due to deformation of the rubber. This is because, to put it more simply, high hysteresis rubbers do not return completely from their deformed to their original shape when the stress is removed. Furthermore, since rubbers are visco-elastic, the rate of deformation is time-dependent. Therefore, the rubber asperity cannot push the other surface back and the resistance of the surface asperity is unbalanced, giving rise to the resistance to motion (Fig. 4).

We now have two elements of the design of a rubber tip required to have increased resistance to friction when in contact with well-lubricated surfaces such as rainy pavement or well-polished floors of a building:

a. use high hysteresis rubbers and rubber compounds;
b. break up the rubber surface by as many edges as practical normal to the surface.

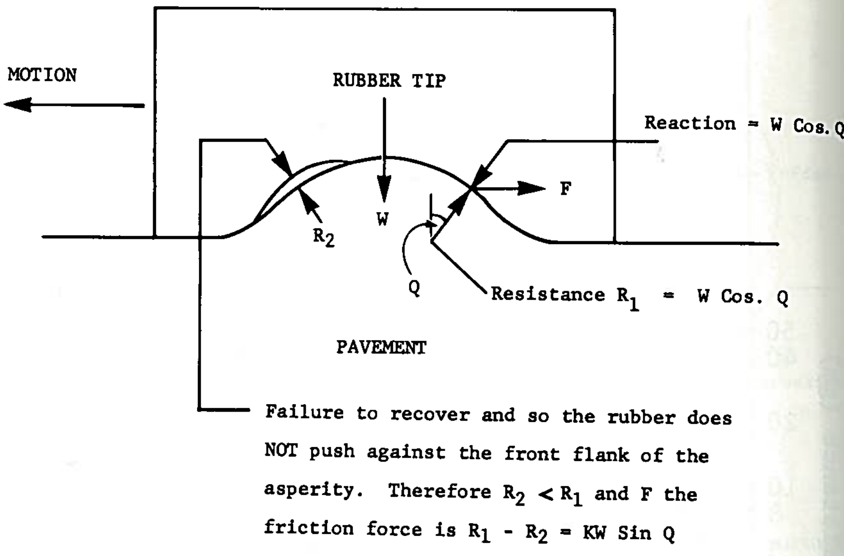

FIGURE 4

THE EFFECTS OF LOW TEMPERATURE, SNOW, AND ICE

The temperature will affect the properties of rubbers, of the other surface, and of any moisture available as lubricant. The results of lowering the temperature are complex and are different for water, ice, and snow. Consequently, no single design of the rubber compound is best for each condition and a compromise is therefore inevitable.

Let us consider first the problem of ice and snow. The friction is markedly reduced as the surface becomes lubricated with water. This can happen with both snow and ice if they are melted either by pressure or by friction due to high velocity sliding. These effects will of course tend to be worst around 0 deg. C. (10); the friction values of dry ice and snow increasing rapidly as the temperature drops below 0 deg. C. This is shown in Figure 5 for natural rubber (NR), and in Figure 6 for styrene-butadiene rubbers (SBR).

Figure 7 shows the skid resistance for natural rubber (NR) and for styrene-butadiene rubber (SBR) tires. The performance of NR is better than that of SBR on dry ice and snow whereas the picture is reversed with wet surfaces at 0 deg. C.–10 deg. C.

Figure 8 shows what happens with oil-extended natural rubber (OENR) and oil-extended styrene-butadiene rubber (OESBR); from this it appears that the better choice for both wet and dry cold conditions is of OENR. This is in spite of the somewhat lower friction coefficient as compared with NR without oil additives.

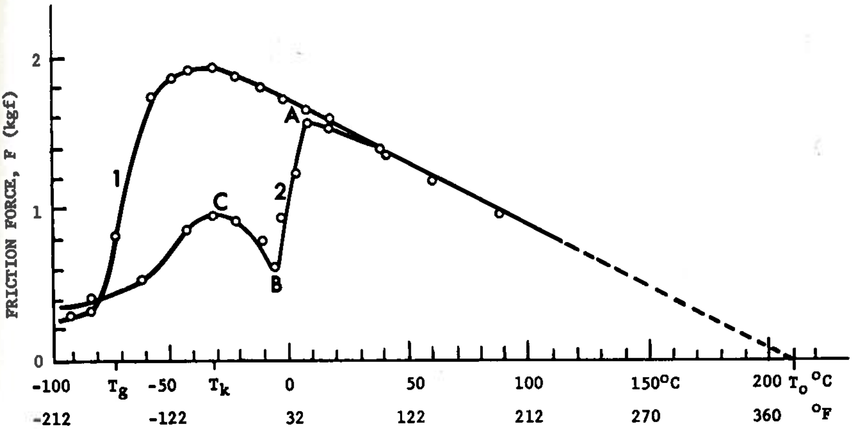

FIGURE 5.—Temperature dependence of the friction force of natural rubber vulcanizates in steady-state friction at normal load of 0.65 kgf/cm.[2] and rate of slip on smooth steel surface 1 mm./min. Curve 1, in vacuum; curve 2, in atmosphere of relative humidity of 50 percent. From reference 10.

Assuming that a patient may put a load of 50 kg. onto a single tip of 4 cm. diameter with a 1 cm. hole removed at the center, the average pressure over apparent surface area is about 4 kg./sq. cm., which is about twice the average contact pressure between an automobile tire and the pavement. The tire has been shown to promote pressure melting of ice and this mechanism cannot be excluded from the crutch-tip case, especially at temperatures around 0 deg. C.

If the crutch-tip does slide, it will achieve some appreciable velocity and this also may well induce melting of the ice to form a water film.

Using reasonable estimates of swing velocity, of walking speed, and of the weight applied to the stick, calculation shows that a 0.1 mm. (0.004 in.) thick water film can be formed by melting the ice.

Experiments with such a film together with practical field experience demonstrate the ability of both tire tread and of our patterned, experimental crutch-tip to cut through water film much thicker than this.

Another interesting parameter is that of the degree of wetting of the rubber by water. In the laboratory this property is measured by the contact angle between the water drop and the material. The higher the angle the less the material is wetted.

Experiments with the resistance of various skis on snow show that it correlates with increasing contact angle. Per contra, it has been suggested (11) that addition of wetting agents to rubber increases the resistance of tires. The literature shows no data on contact angles for various types of rubber or of rubber formulations and no other data exist to correlate its degree of wetting with frictional behavior. This is not surprising,

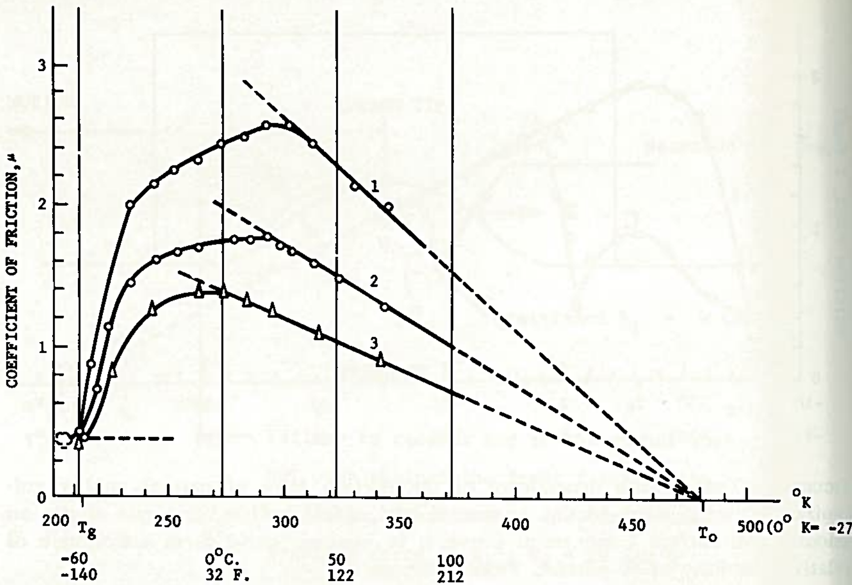

FIGURE 6.—Temperature dependence of the coefficient of friction of vulcanizates of SKS-30 butadiene styrene copolymers at rates of slip 1 mm./min. and three normal loads. Curve 1, 0.15 kgf./cm.^{2}; Curve 2, 0.65 kgf./cm.^{2}; Curve 3, 2 kgf./cm.^{2}. From reference 10.

since rubber surfaces are really quite impossible to define. As molded they may be smooth; the surface soon changes on exposure to air, some ingredients bloom to the surface in time and abrasion dramatically changes the nature of the surface.

One could explain the apparent contradiction between the results quoted with skis and those for rubber by suggesting that addition of wetting agents would reduce the surface tension of a water film and therefore reduce also the energy required for a rubber asperity to break through the water layer to make contact with the pavement. A ski, without rolling friction, cannot do this and the adhesion force mechanism would dominate. This is reduced as the contact angle increases.

The friction with *dry* snow at very low temperatures (where local melting is unlikely) is, as Bowden and Tabor (12) observe, about the same as that observed for dry sand. Their results were for skis, some plastic coated, and not for rubbers, but their general remark is true for rubbers, namely that the results will now depend on the nature of the solid-solid friction.

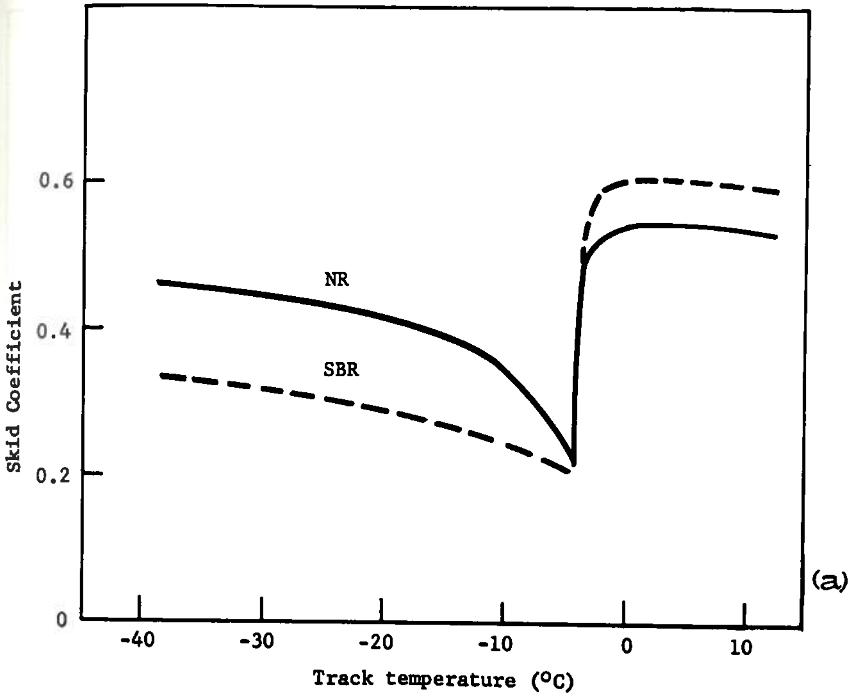

FIGURE 7.—From reference 14.

IMPROVED DESIGN OF RUBBER CRUTCH-TIPS

On the basis of the foregoing we can now design both the rubber compound and the geometry of the tip to suit wet pavement, dry snow, dry ice, and wet ice-water surfaces. Ideally, each of the designs would be of the same geometry but made of different rubber formulations. This would clearly be unrealistic since each of these conditions rarely can be predicted to last for a long time. In practice they occur within the same weather span in most countries.

A compromise design is therefore necessary and has been used for the experimental tips now undergoing extensive user trial.

Enough has been exposed in this paper for specific formulations to be designed for cases such as dry ice and snow, in locations with several months of outdoor temperatures below say —10 deg. C. and where it can be ensured that the temperature does not rise till the final thaw.

Geometry

This must present the maximum practical number of edges at the surface. Ideally, they should be cut edges close to each other, but consideration of economic mass production may force the use of a molded

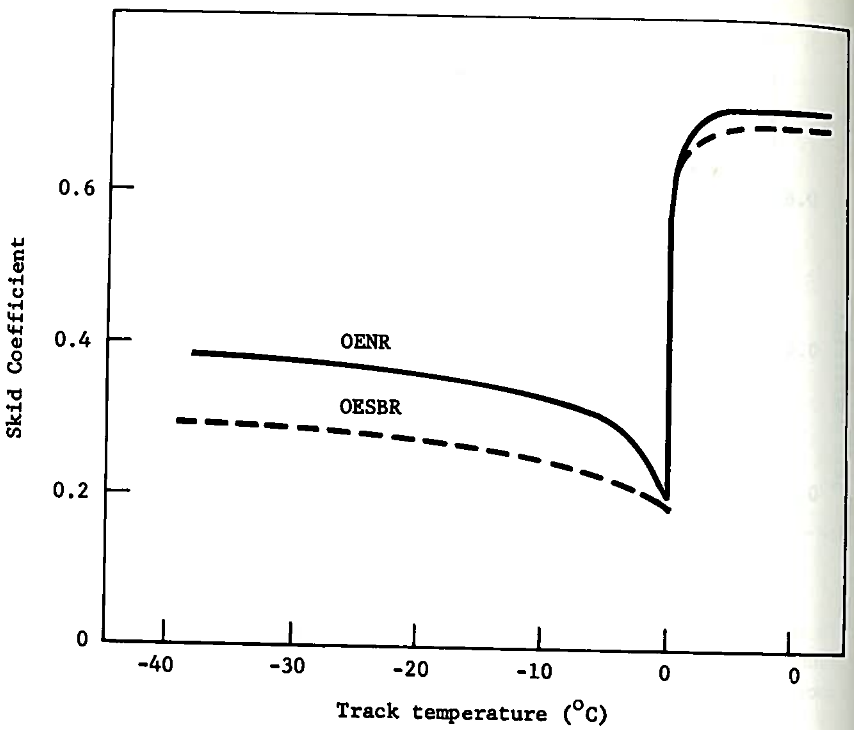

FIGURE 8.—From reference 14.

tread. The base should be flat and with no protuberances at the center (Fig. 9). To obtain an improvement with existing crutch-tips, users could perhaps be encouraged to slice the base radially.

This geometry will promote penetration of water films, it increases friction due to deformation of the tip, allows the hysteresial properties of the rubber maximum effect, destroys the vacuum that would be caused by a continuous fluid film, and decreases the chances of slip due to scraps of leaf covering the whole surface of the base.

It also allows the base to absorb some torsional strain, without causing overall movement of the tip which gave anxiety to some users of an early mark of the new tip. Another interesting factor, which confirms the choice of NR and SBR for high skid resistance, is given by the approximately inverse correlation between water vapor transmission and skid resistance for various rubbers (13) (Fig. 10).

Design of Rubber Compounds

Rubbers should be soft rather than hard, as with present tips; the hardness should be well below 70 Shore; 50 has been used for our experiments and has proved suitable so far. The effect is dramatic

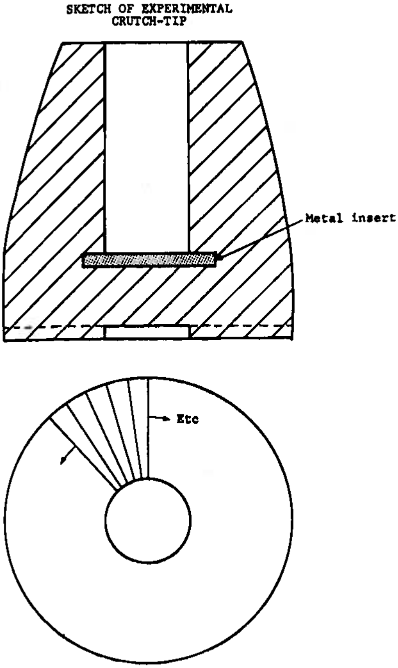

FIGURE 9

(Fig. 11). So far as fillers are concerned high carbon black loadings reduce frictional resistance. This is of no importance to crutch-tips since the use of carbon black is to be avoided in order to avoid marking the floors.

Use of other fillers based on silica or clay is usual in crutch-tips, because they do not mark the floor. The use of such fillers in 5–25 percent proportion to rubber is valuable in order to obtain a reasonable hardness and abrasion resistance while permitting a relatively low cross-link density. Silica fillers also tend to increase the hysteresis of the rubber compound.

Choice of rubbers is partly determined by their glass transition temperature, which is the temperature above which the material behaves as a rubber and below which it corresponds to a brittle solid.

The best properties relative to temperature are given when the use temperature is between 85 deg. C.–90 deg. C. above the glass transition temperature.

A low cross-link density is better than a high one over the whole temperature range. The detailed chemical methods of obtaining cross-link density are important. These include choice of curing agents, effect of polar groups and side chains in the polymer structure and their glass-transition temperature, as noted above.

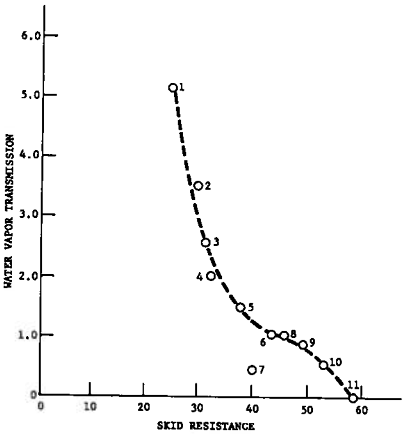

FIGURE 10.—Correlation between water vapor transmission and skid resistance on glazed tiles. 1-BR (high cis); 2-Solution BR (low cis); 3-BR 70/NR 30; 4-BR 50/NR 50; 5-BR 20/NR 80; 6-NR; 7-EPR; 8-SBR 1712 58/BR (high cis) 42; 9-SBR 1500; 10-SBR 1712; 11-NR. From reference 13.

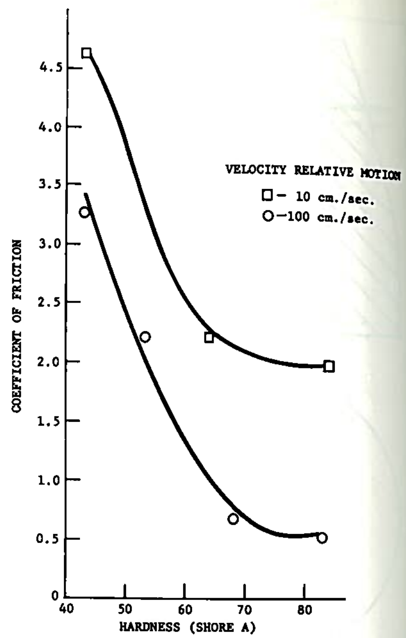

FIGURE 11.—Natural rubber—coefficient of friction vs. hardness.

It has been conclusively shown that the rubbers must have high hysteresis to promote high friction in any circumstances of solid friction. The effect of lowering the temperature, in the range of interest, is to increase the hysteresis, which is fortunate.

Suitable rubbers are natural rubber (NR) and styrene butadiene rubber (SBR), especially below 0 deg. C. Around the freezing point of water, oil extension of either gives better frictional properties on wet films, preference on balance over the 0 deg. C–10 deg. C range going to OENR. Over the range the compromise goes to OENR, but excellent results have also been obtained with OESBR (14) in tires and in our experimental crutch-tips. Such compounds have good long-term properties and have an adequate resistance to abrasion.

Testing

This section is an unashamed explanation of the absence of what many workers may have expected—a detailed and carefully simulated laboratory test.

Experience with vehicle tire testing and with testing of walking procedures has shown the extreme difficulty of devising a test at all and then of correlating the results with field performance.

Vehicle tires designed for similar conditions are tested on a skid-resistance unit trailed behind a standard car (14).

The causes and measurement of walkway slipperiness were investigated by the National Academy of Sciences (U.S.A.) and the results were inconclusive (15).

The mechanics of using tips on sticks, crutches, and other walking aids are far more complicated and individual than those of normal walking, let alone of driving an automobile on rubber tires on conventional pavements.

It is therefore concluded that no laboratory simulations of the friction behavior of the complete tip are worthwhile. As we observed at the beginning of this paper Leonardo da Vinci did not test his assertions either—we are in good company. Furthermore, we may place some considerable reliance on the theoretical explanations of the behavior and design of materials and of the geometry, which is supported by an abundance of experimental evidence, presented in essence here.

The improved tips made according to the theoretical and experimental considerations have been tested by various users in Stoke Mandeville Hospital and by other stick and crutch users in the United Kingdom and the United States. Their criticisms have been incorporated in the various stages of development. The latest versions are available from the Zimmer Orthopaedic Co. These will still be, temporarily, in the same mold as their previous design.

The new tips are now available for the best test of all: more widespread use by patients and return of their comments.

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