Subjective Scaling of Smooth Surface Friction

ALLAN M. SMITH AND STEPHEN II. SCOTT
Centre de Recherche en Sciences Neurologiques, Département de Physiologie, Université de Montréal, Montreal, Quebec H3C 3T8, Canada

SUMMARY AND CONCLUSIONS

1. Six men and four women, 30-51 yr of age, were asked to use the tip of the washed and dried index finger to stroke six different featureless, flat surfaces mounted on a three-dimensional force platform. The six surfaces were rosin-coated glass, glass, satin-finished aluminum, poly-vinyl chloride (PVC) plastic, Teflon, and nylonprint (polyamide plastic). The subjects were requested to indicate where the sensation produced by each surface should be placed on an unidimensional scale represented by an 18-cm line labeled at one end by the words "most slippery" and at the other end by the words "most sticky." The coefficients of friction for each surface and for each subject were subsequently assessed by asking each subject to stroke the surfaces as if they were assessing its slipperiness for 5 s.

2. The finger forces normal and tangential to the stroked surfaces were digitized at 250 Hz and stored on a laboratory computer. The ratio of the mean tangential force to the mean perpendicular force during stroking was used to calculate the mean coefficient of kinetic friction. The mean friction for all subjects ranged from 0.43 for the nylonprint surface to 7.79 for the rosin-coated glass. Correlation coefficients calculated between the subjective estimates of friction and the measured coefficients of friction for each subject individually resulted in a mean correlation of 0.85 (n = 10, P < 0.001).

3. These data indicate that subjects can accurately scale relative differences in the friction of macroscopically smooth, flat surfaces, by modulating the tangential force applied to the finger while keeping the normal force relatively constant. The fact that subjects maintained a relatively constant normal force and instead varied the tangential force across different surfaces suggests that receptors sensitive to these tangential forces are important in the perception of smooth surface friction.

INTRODUCTION

Although friction may be a somewhat underestimated aspect of somesthesia (Smith 1994), it has been studied from at least two distinctly different perspectives; first, as an important parameter in prehensile force control and, second, as a perceptual dimension of active touch. Johansson and Westling established that grip forces are adjusted to the coefficient of friction of different surfaces of grasped objects (Johansson and Westling 1984a; Westling and Johansson 1984). They also demonstrated that when subjects washed and dried their hands, skin friction was reduced, resulting in a need for greater prehensile force to lift and hold the same object against the force of gravity (Westling and Johansson 1984b). In a subsequent study specifically designed to dissociate the effects of texture and friction on grip force control, it appeared that friction, not texture, was the parameter of primary importance (Cadoret and Smith 1996). Moreover, the subjects in these experiments were well aware of the presence of adhesive and lubricating films used to change the frictional properties of the textures employed.

In contrast, research into the perception of skin friction, largely conducted by the cosmetics industry, has identified certain stimuli that influence the friction of skin and that also contribute to the subjective sensations of skin smoothness, greasiness, and moistness. However, these studies never explored the psychophysical relationship between perceived and real friction directly. For example, Appeldoorn and Barnett (1963) determined that the coefficient of friction of skin against some surfaces such as rubber could be as high as 2.0, but that this could be reduced by the introduction of emollients. Other studies demonstrated that skin friction increases with hydration and decreases with films such as talcum powder and silicone oil (El-Shimi et al. 1977; Naylor 1955). Wolfram (1983) pointed out that because of its compliant viscoelastic properties at low contact forces, the friction of skin does not strictly obey the linear force-load relationship known as Amontons' law. This observation has important implications for the perception of friction at the low level forces used in active touch as compared with grasping force control that generally employ much higher contact forces.

The primary objective of most of these cosmetic industry studies was to demonstrate that changes in the friction of skin on skin was detectable by stroking the test region with the fingers. The broader questions about how well the skin can detect the friction of surfaces other than itself, and what skin receptors mediate the sensation of friction were never fully addressed.

Friction has been either an overt or covert variable in many psychophysical investigations of the spatial features of surface textures contributing to the subjective sensation of roughness (Connor et al. 1990; Connor and Johnson 1992; Ekman et al. 1965; Lamb 1983; Sathian et al. 1989; Taylor and Lederman 1975). For simplicity, texture may be defined as the macroscopic surface irregularities measured in units of average distance between the peaks and valleys with a profilometer or similar device. Kinetic friction, on the other hand, refers to the ratio of a tangential sliding force to a perpendicular load force (Bowden and Tabor 1982). Ekman et al. (1965) investigated the ability of subjects to scale the roughness of different grades of sandpaper and concluded that roughness was a power function of the coefficient of friction. No indication was given as to how friction was measured in this study, or whether the friction was static or kinetic. These results were later questioned by Taylor and Lederman (1975), who found that randomly adding liquid detergent to six grooved test surfaces had no effect on the ability of subjects to scale the subjective surface roughness.
Although most subjects preferred to use a back and forth motion touch all the surfaces with the index finger as often as they desired. The principal subjective dimensions of smooth-rough and hard-soft (Hollins et al. 1993) asked subjects to sort 17 tactile adjectives used to described the surfaces. They suggested that, although a slippery-sticky dimension might be one component in the multidimensional subjective experience of texture, it could not be adequately differentiated from the two principal subjective dimensions of smooth rough and hard soft (Hollins et al. 1993). They concluded, not unreasonably, that high friction is associated with roughness, and low friction with smoothness in the minds of most subjects. The aim of the present study was to determine whether subjects are able to consciously scale surface friction when they are confronted with flat, smooth surfaces where the macroscopic geometry is not a confounding variable.

METHODS

All subjects were unpaid students or faculty at the Université de Montréal who consented to participate in the study. Subjects were asked to wash and dry their hands 5 min before starting the experiment. In this experiment, four women and six men (ages 30-51) were asked to use the tip of the index finger to stroke six 8 X 3-cm smooth surfaces mounted on a three-dimensional force platform (F/T, Assurance Technologies). The six macroscopically featureless, flat surfaces were composed of rosin-coated glass, glass, satin-finished aluminum, poly-vinyl chloride (PVC) plastic, Teflon, and nylonprint (polyamide plastic).

Before each test session, all the surfaces were cleaned with alcohol and dried. For one of the surfaces, a thin coating of rosin-lacquer thinner solution was applied to a microscope cover glass and allowed to dry for 10 min. The dried rosin gave the smooth glass a tacky sensation to the touch. Each subject was given a familiarization phase in which they had the opportunity to see and touch all the surfaces with the index finger as often as they desired. Although most subjects preferred to use a back and forth motion of the finger, they were instructed afterward to stroke the surfaces using left to right sweeps in a single direction perpendicular to the long axis of the index finger. The subjects were free to use the velocity of their choice to stroke each surface with the same finger in a predetermined pseudorandom order.

Each subject was then asked to indicate where the sensation produced by each surface should be placed on a visual analogue scale (VAS) represented by an 18.0-cm line labeled with the words "most slippery" on one end and "most sticky" on the other. A new scale was provided for each surface. The subjective estimates of friction were quantified by measuring the distance along the 18-cm line indicated by each subject for each surface.

The kinetic friction of each surface was subsequently evaluated by asking the subjects to stroke the surfaces for 5.0 s again with the index finger as if they were assessing its slipperiness. Because the degree of moisture on the skin varies greatly between subjects and has a significant effect on the skin-surface friction (see Johanson and Westling 1984b), it was important to obtain an estimate of friction for each subject on each surface. The forces and torques recorded by the load sensors as the subjects stroked each surface were digitized at 250 Hz (resolution for force was 0.0006 N/unit and for torque was 0.0006 Nm/unit) and stored on a laboratory computer. The signals were filtered with a double-pass Butterworth filter with a cutoff frequency of 25 Hz (Winter 1990). The position and instantaneous velocity of the subject’s fingertip were not computed directly. Instead, the center of pressure of the fingertip on the force plate was computed and its velocity derived (see Winter 1990 for details of methods). The finger forces, and velocity as well as the coefficients of friction were first displayed graphically using MATLAB software. The instantaneous coefficient of friction was computed by dividing the tangential force by the normal force. The mean coefficient of kinetic friction for each surface was computed by averaging the instantaneous coefficient of friction when the contact force of the fingers exceeded 0.10 N and the finger velocity was >5.0 cm/s for a distance of 5.0 mm. These cutoff criteria removed the transients associated with starting and stopping the finger movement at the initial and terminal phases of the stroke.

RESULTS

The graphic display of the normal and tangential forces from a single subject stroking an aluminum surface is shown.
SUBJECTIVE SCALING OF FRICTION 1959

A

SUBJECTIVE FRICITION

KINETIC FRICTION

Rosin Glass Plastic

SURFACES

B

SUBJECTIVE ESTIMATE (cm)

KINETIC FRICTION

Nyloprint Aluminium Glass Rosin Glass

C

SUBJECTIVE ESTIMATE (cm)

KINETIC FRICTION

in Fig. 1. It can be seen that the perpendicular contact force remained between 0.20 and 0.30 N in this subject. These normal forces rarely exceeded 1.0 N in any subject. Each subject adopted a preferred stroking velocity that varied between 8 cm/s for the slowest subject to 26 cm/s for the fastest subject with a mean of 15.6 cm/s. However, the stroke velocity for a given subject remained within a narrow range (±4.2 cm/s, SD). The mean coefficient of friction for each surface was computed from the average ratio of the instantaneous tangential force divided by the normal force during the stroking movement. Graphically the kinetic friction can be displayed as the linear relationship between the normal and tangential forces. Figure 2 shows the kinetic friction for a single subject stroking glass (a high friction surface) and nylonprint (a low coefficient surface). The slopes, which are equal to the inverse coefficient of friction, of these force relationships are clearly different.

The mean coefficient of friction for each of the six surfaces is shown in Fig. 3A. It can be seen that despite a fairly wide range of coefficients of friction tested, the coefficients of some of the surfaces were similar. Although a one-way analysis of variance used to test for differences in friction among the six surfaces indicated significant differences in surface friction (F = 28.98, P < 0.001), a pair-wise comparison test subsequently showed that the PVC plastic surface was not significantly different from aluminum, and that Teflon was not significantly different from Nylonprint. For this reason the plastic and Teflon surfaces were not included in the comparison of the subjectively ranked estimates of friction with the coefficients of kinetic friction calculated from the ratio of tangential to normal forces shown in Fig. 3B.

The scatter of individual judgments seen in Fig. 3B indicated differences in the subjective friction ratings among the 10 individual subjects. Figure 3C shows the same data as Fig. 3B plotted on a log scale and with the data points for each subject connected and demonstrates that, in general, subjects scaled friction accurately. There were only 2/40 errors or reversals in the VAS ratings of surface friction. That is, individuals seemed to be consistent in their relative judgments of the surface friction, but the absolute value of their estimations when measured on a common parametric scale varied in comparison with each other. It was therefore decided to calculate individual correlations between the subjective friction estimates based on the VAS and the measured coefficients of friction for each of the 10 subjects. These individual correlations were z-transformed and averaged across all subjects. The mean correlation for all subjects and all six surfaces was r = 0.85 (n = 10, P < 0.001). Because the glass and rosin covered glass had higher coefficients of friction than most commonly encountered objects, we recalculated the correlation between the ranked friction estimates and the measured friction for each of the 10 subjects without these surfaces. However, the correlation (r = 0.76,
Because most subjects appeared to be able to scale the friction of flat, macroscopically smooth surfaces accurately, we wondered what strategies of force modulation would be most likely to provide this information? We therefore compared the dynamic modulation of tangential and normal forces over a range of kinetic frictions. Figure 4A shows that tangential forces were subjected to considerable modulation in all 10 subjects, whereas Fig. 4B shows that the normal forces were subjected to little or no modulation. Although there was no instruction to do so, subjects may have estimated friction from sensations arising from the tangential stroking force while the normal force was held relatively constant over the range of frictions examined.

Although most subjects yielded reliable and consistent coefficients of friction while stroking the test surfaces, occasionally, in three subjects we observed systematic short-term increases in friction that could not be explained by systematic changes in normal or tangential stroking forces or by changes in stroking velocity. Figure 5 illustrates an example of a substantial increase in skin friction as a subject stroked a PVC plastic surface. That is, the coefficient of friction increased with each successive sweep of the fingertip over the surface, and despite what appeared to be random fluctuations in the normal and tangential force, the friction increased in an orderly manner from 0.36 to 0.79. These sporadic increases were rare and were not reliably related to either individual subjects or particular surfaces. For these few cases we calculated the mean kinetic friction in the same manner. We know that sweat release can substantially increase the skin-surface friction (Adams and Hunter 1969; Johansson and Westling 1984b), but we do not know what effect this changing friction may have had on the subjective estimates.

DISCUSSION

The results support the notion that when subjects are given the opportunity to make magnitude estimates about the frictional properties of smooth, flat surfaces, they are able to scale friction with a reasonable degree of accuracy. This observation does not alter the fact that in everyday experience, rough, textured surfaces have higher coefficients of friction than smooth surfaces.

In spite of the fact that the smooth surfaces used in the present study differed in other respects besides their coefficient of friction, it seems unlikely that these differences could account for the results. For example, although each surface differed in color and position on the force platform, it is difficult to imagine that vision played any role other than to position the finger on the test surface. Also, differences in heat conductance among the materials was not systematically associated with either high or low friction, and the relatively low level of perpendicular forces used by the subjects makes discrimination based on differences in surface hardness seem equally improbable.

The normal forces used to stroke the surfaces ranged between 0.20 and 1.0 N, values compatible with those typically found in other studies of tactile discrimination of textures in human subjects (Lamb 1983; Morley et al. 1983; Phillips et al. 1992). The measurements of the compliance of the index finger skin by Westling and Johansson (1987) indicate that the skin is most elastic in this range of forces, and it ceases to be compliant beyond a force of ~1.0 N. According to El-Shimi et al. (1977), the skin friction is enhanced by its elastic compliance, and therefore it would appear that in active touch the normal forces are adjusted to the compliance of the skin to maximize the friction of the skin to an explored surface.

A surprising finding of the present study was the transient increase in skin friction observed with some subjects on some surfaces. Measurement of the separate normal and tangential forces failed to show any systematic changes that could account for the regular and incremental increase in friction. Heat generated by the kinetic stroking might have evoked sweat secretion that would have increased the measured friction. However, this explanation seems unlikely be-
because the short term changes in friction were not associated with either the surfaces with the highest friction or with highest levels of normal and tangential forces. This would have been expected because these conditions would have generated the greatest warmth on the fingertip. Nevertheless, increased sweating does appear to be the most logical explanation for the increased friction. It appears as if stroking the surface may have triggered sweat release on the fingertip, although to the best of our knowledge, there is no physiological evidence to suggest such a mechanically triggered sudomotor reflex exists.

In our experience, the use of lubricating films to reduce friction in active touch must be done with caution. A preliminary investigation (Cadoret and Smith 1996) indicated that petroleum jelly applied between smooth nyloprint and the finger was a powerful lubricant when the normal forces on the skin exceeded 3.0 N. However, this same substance acted as an adhesive at the skin-nyloprint junction for the very low (0.20–0.30 N) normal forces used by most subjects in the present study. Variations in skin moisture constantly cause changes in the coefficient of friction of the skin, and any increase in skin slipperiness would require a corresponding increase in prehensile force to hold an object against gravity (Johansson and Westling 1984b). In retrospect, it would have been advisable to pay more attention to standardizing the stroking pattern and velocity because fingertip skin may be anisotropic. Tangential forces directed proximally along the long axis of the finger meet greater friction than distally directed forces (Jones and Hunter 1992). In this study the tangential forces were directed perpendicular to the long axis of the finger from left to right in all our right-handed subjects, but no systematic attention was paid to directional differences in the frictional properties of the fingertip skin. The possibility of directional differences coupled with the moment to moment changes in skin friction due to sweat secretion suggest that subjects are more likely to perceive and scale relative changes in friction rather than absolute differences.

The data from the present study show that when the countaining effects of surface asperities are removed, subjects are able to accurately assess the friction of smooth surfaces by stroking the finger over the test surface. The uniformly wide dynamic range of the tangential force modulations compared with the limited variations in the normal forces suggest that a common strategy was employed by most of the subjects. That is, most subjects controlled the stroking movement such as to maintain a constant contact force, therefore coupling surface friction and tangential force. This strategy would favor a perception of friction based largely on a comparison of the tangential forces created while stroking the finger over the test surfaces and suggests that slowly adapting type II mechanoreceptors, which are known to be sensitive to tangential forces, might be the most likely source of this information (Edin 1992; Knibestol and Vallbo 1970; Srinivasan et al. 1990; Westling and Johansson 1987). However, Macefield et al. (1990) found that stimulating small fascicles of slowly adapting type II receptors failed to produce conscious sensations on 15/18 occasions. Possibly a larger number of slowly adapting type II receptors need to be recruited in order to produce conscious sensations. Further research involving the microneurographic recording of the responses of slowly adapting type II receptors to sliding smooth surfaces with differing frictions across the skin would contribute greatly to our understanding of the neurophysiological mechanisms responsible for the sensation of friction. Whatever the mechanisms involved, the contribution of friction to tactile perception may have been dismissed prematurely. The perception of friction would appear to be an important dimension of somesthesia serving both the sensory and motor functions of the hand.

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Address for reprint requests: A. M. Smith, Centre de Recherche en Sciences Neurologiques, Dept. de Physiologie, Universite de Montreal, Case postale 6128, Succursale Centre Ville, Montreal, Quebec H3C 3T8, Canada.

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