Friction, Not Texture, Dictates Grip Forces Used During Object Manipulation

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

SUMMARY AND CONCLUSIONS

1. Three men and seven women, 25-40 yr of age, were asked to use the thumb and index fingers to grasp, lift, and hold the armature of a linear motor generating a 2.0-N opposing force (simulating an object weighing ~200 g) for 2 s. The surface in contact with the fingers was composed of smooth or polyamide plastic etched with 1.0-mm high Braille beads separated at 2.0- or 3.0-mm intervals measured from apex to apex. The surfaces were left either untreated or coated with talc, water, or sucrose films designed to change the coefficient of friction with the skin. Talc reduced the coefficient of friction, whereas water and sucrose both increased the friction against the skin. In all, 12 surface conditions were used to evaluate the effects of texture and friction on the grip force during lifting and holding.

2. For all subjects the inverse coefficient of friction was associated with proportionately scaled increases in grip force, regardless of surface texture. The peak lifting force as well as the static force used to hold the object stationary were significantly correlated with the inverse of the coefficient of friction. When coatings were applied to dissimilar surface textures to produce similar coefficients of friction, the grip force profiles were nearly identical. When strong adhesives increased the friction of the smooth surface compared with textured surfaces, grip forces decreased as friction increased. That is, although the untreated smooth surface had less friction than either of the two textured surfaces, the addition of sucrose increased the smooth surface friction to a higher level than either of the similarly treated textured surfaces. As a result, the effect of surface friction could be dissociated from the effect of either surface texture or coating. Friction appears to be a more important factor in determining the grip force than either texture or surface films at least for the range of textures and coatings examined in this study.

INTRODUCTION

A recent review suggested that friction was a neglected parameter of somesthesia (Smith 1994). This may be due in part to the controversial contribution of friction to the scaling of roughness, which has been both affirmed (Ekman et al. 1965) and denied (Taylor and Lederman 1975). To avoid confusion, the terms roughness, texture, and friction need to be carefully distinguished. In the present study the terms roughness or smoothness are used to refer to the subject's sensations arising from a haptic perceptual process. In contrast, texture is defined as a physical parameter described in terms of the size and spacing of macroscopic surface structures that may be measured with an instrument like a profilometer. Friction, which is also a physical parameter, is defined as the minimal force needed to initiate or maintain sliding of a given weight on a particular surface. The coefficient of static friction is the ratio of the tangential force to the normal force ($\mu = F/W$), where $\mu$ is the coefficient of friction, $F$ is the tangential force needed to initiate motion, and $W$ is the normal force (Bowden and Tabor 1982; El-Shimi 1977).

For solid surfaces the friction is proportional to the normal force and is independent of the contact surface area. However, compliance of the skin can increase the coefficient of friction against a solid surface at low contact forces (Wolfram 1983), although it can be shown for fingertip skin, that the area of contact reaches a plateau at $\sim 1.0$ N (Westling and Johansson 1987). Because all the grasping forces in the present study exceeded this level, the coefficient of friction was considered independent of contact area, justifying the use of the standard equation to calculate the coefficients of friction.

Support for the importance of friction in somesthesia comes from studies of grasping that have shown that the grip force is adjusted to the friction between the object surface and the skin of the fingers. These investigations have been largely pioneered by Johansson and Westling, who first suggested that grip force was adjusted to the coefficients of friction of different surface textures such as silk, suede, and sandpaper (Johansson and Westling 1984a,b; Westling and Johansson 1984). Blocking cutaneous sensation from the fingers by applying local anesthetic to the digital nerves severely disrupted the adjustment of grip force to surfaces with different textures and coefficients of friction. Although these investigators repeatedly demonstrated clear differences among surfaces, there was actually only one published instance in which friction was altered for the same contact surfaces (Johansson and Westling 1984b). This study demonstrated that, when the subjects had just washed and dried their hands, skin friction was greatly reduced and an increase in grip force was noted. With repeated grasping, the sweat accumulating on the skin increased adhesion to the grasped surface, which was accompanied by a commensurate decrease in grip force. The present study was designed to examine the effect of changing the coefficient of friction for the same smooth and textured surfaces by adding surface lubricants and adhesives.

METHODS

The three men and seven women (ages 25-40) who consented to participate in the study were asked to grasp a test object, and to lift it and hold it stationary for 2 s. The object to be lifted was the vertically mounted armature of a linear motor, which, in the
present study, generated a 2.0-N downward force simulating a free-standing 200-g weight. However, when the linear motor was inactivated, the armature actually weighed 674 g and had an inherent static friction of 0.44 N. Although the linear translation of the motor was minimized by low friction roller bearings, the inherent kinetic friction was probably not significantly less than the static friction and undoubtedly contributed some resistance to lifting. A sketch of the apparatus is shown in Fig. 1A. The subjects were asked to grasp two identical circular disks between the thumb and forefinger of their preferred hand, and to carefully lift the disks to a height of 2.5 ± 1.0 cm for 2.0 s. The correct height was indicated to the subjects by a light and a 1.0-kHz pure tone. Subjects were also instructed not to pull, push, or twist the manipulandum but to lift the object applying a vertical force only. The grasped object was equipped with a position transducer, accurate to 0.5 mm, and two precalibrated load cells mounted in tandem alignment between the grasping disks and the motor armature. One load cell measured the horizontal grip force, and the other measured the vertical lifting force. The voltages corresponding to the forces applied over a 30-N range were digitized with a 12-bit converter at 250 Hz and stored on disk by a laboratory computer.

The test surfaces in contact with the fingers were either identical pairs of smooth or etched polyamidic plastic textures. The two etched surfaces were Braille heads 1.0 mm high and evenly spaced
at either 2.0 or 3.0 mm intervals from apex to apex. In addition to the untreated polyamide plastic, three coatings were used to alter the coefficients of friction against the skin. These consisted of talc (a dry lubricant), distilled water, and 30% sucrose (both adhesives). In spite of these coatings, all three surfaces could be readily discriminated from one another.

Subjects washed and dried their hands before each new condition. Each combination of texture and surface coating was repeatedly presented in blocks of 10 trials, and the lubricant or adhesive coatings were renewed between trials. On separate 10-trial blocks immediately following measurements of the grip force, the subjects were required to release the test object slowly in order to determine the slip point for all conditions. Some practice was also needed to enable subjects to release the object gradually. The slip point was defined as the first detectable change in position even if the object’s fall was subsequently arrested, as frequently happened with high friction surfaces that tended to stick and slip. The load force divided by the grip force at the moment of slip yielded the coefficient of friction for a single trial, and the 10-trial average represented the coefficient of friction for a single surface condition. When the smooth surface was treated with sucrose, the object failed to slip reliably with the 2.0-N test force, so the force was increased to 5.0 N to measure friction with this coating. Otherwise, the sucrose was so adhesive it would have allowed subjects to raise and hold the object without applying any grip force whatsoever. However, all subjects in fact applied some force to the object for all textures treated with sucrose. Figure 1B illustrates the mean grip, and load forces and displacement traces averaged for 10 trials by a single subject lifting a 2.0-N opposing force while grasping a polyamide plastic surface etched with 1.0-mm high beads spaced at 2.0-mm intervals and coated with talc, water, or sucrose or left untreated. The mean grip, load, and displacement traces have been aligned on the first detectable change in grip force by a computer in order to facilitate a comparison of the grasping, loading, and lifting events. However, the trailing events associated with releasing are desynchronized, and their relationship with respect to one another is meaningless. The lifting velocities in the present study were somewhat greater than those of Johansson and Westling (1984a,b), and therefore the falling load force after the object reached its peak vertical height is due to the decelerative braking force used to prevent overshooting the position window.

RESULTS

Figure 1C illustrates the mean grip force applied by a single subject while grasping, lifting, holding, and releasing the same 2.0-N force for all 12 combinations of textures and coatings. The force traces were aligned on the first detectable change in grip force (grip onset). It can be seen from Fig. 1C that both the peak dynamic force and the static grip force increased markedly for the slipperier surfaces and decreased with increased friction.

Coatings or textures were only effective at changing the grip force insofar as they were able to influence the coefficient of friction. Figure 1D demonstrates that for a single subject, both the untreated 2- and 3-mm textures (top traces) and the same textures coated with talc (middle traces) had different coefficients of friction, and that the grip force was always higher whenever the friction was lower. When the 2- and 3-mm textures had equal coefficients of friction produced by adding talc to the 3-mm surface, then the grip forces were nearly identical (bottom traces). Although not identical for all subjects, the grip forces were similar whenever the coefficients of friction were similar.

The mean coefficients of friction averaged for the 10 sub-

... for the various surface conditions and textures used in this study are illustrated in Fig. 2A. For the talc coating and dry surface, friction increased as a function of increasing texture from smooth to the 2- and 3-mm bead spacing. Moisture appears to have been just adhesive enough to eliminate the differences in friction among the three textures, and, as seen in Fig. 2A, the smooth surface coated with sucrose had a higher coefficient of friction than either similarly treated 2- or 3-mm textures. Coatings of petroleum jelly (a lubricant), and rosin (an adhesive) were also tested in a separate group of five subjects, although these data are not shown. As expected, petroleum jelly frequently reduced the coefficient of friction of the smooth surface to <0.20 but had less effect on the 2- or 3-mm surfaces. In both these extreme conditions, the grip force remained correlated with the inverse friction. Taken together, these observations indicate that subjects react to changes in friction as distinct from changes in either texture or coating, and therefore it is likely that friction is the more critical factor dictating grip force.

Figure 2, B and C, shows that, for all 10 subjects, both the mean peak grip force during lifting, as well as the static grip force during stationary holding measured over the final 500 ms before release, were adjusted to the coefficient of friction. These results confirm and support those of Johansson and Westling (1984a,b) that the lower the coefficient of friction, the greater the grip force applied during lifting and holding.

Three separate 2-way analyses of variance were performed on the coefficients of friction, the mean peak force, and the mean static force generated by all 10 subjects for the 12 different combinations of textures and coatings. Surface coating had a significant main effect on friction and on both peak and static force (P < 0.001). However, texture alone did not significantly affect either the friction or the grip forces, although a texture by coating interaction was statistically significant (P < 0.001). This interaction occurred because the beaded surfaces had a higher coefficient of friction than the uncoated or talc lubricated smooth surface, but when the same surfaces were covered with the adhesive sucrose, the beaded textures had lower coefficients of friction than the similarly treated smooth surface. The dynamic and static grip forces reflected similar patterns (Fig. 2, B and C). The most probable explanation for the texture by coating interaction is that the smooth surface provided a greater contact area for both the lubricant and adhesive coatings, thereby enhancing both the lubricating or adhering properties compared with either of the textured surfaces.

The grip forces applied to highest and lowest friction surfaces were frequently identical in the initial phases. That is, the separation in the grip forces only appeared after the initiation of the lifting or load force. Figure 2D shows the average initial grip and load forces and the initial displacement traces for a single subject lifting smooth plastic surfaces coated to produce either high or low coefficients of friction. Both the high and low friction conditions were aligned on the grip force onset. The rates of grip force application began to diverge after the initiation of the lifting as if they were triggered by stimuli generated by these tangential
FIG. 2.  A: histogram of the mean (±1.0 SD) coefficients of friction of 3 surface textures and 4 surface conditions for 10 subjects averaged together.  B: mean (±1.0 SD) peak dynamic grip forces of 3 surface textures and 4 surface conditions for all 10 subjects.  C: mean (±1.0 SD) static grip forces used to hold a 2-N opposing force with 3 surface textures and 4 surface conditions for all 10 subjects measured on the last 500 ms before object release.  D: 10-trial average of initial grip and load forces and displacement traces for a single subject lifting surfaces with high and low friction. Top ordinate shows the force traces, whereas the bottom ordinate shows the lifting distance in mm, and all traces have been aligned on the grip onset (time 0).  E: changes in grip and load force coordination during lifting of the same smooth surface with 4 different conditions altering the coefficient of friction shown for a single subject.  F: mean static grip forces (▲) and the mean slip forces (●) for all subjects for a range of inverse coefficients of friction. The regression line drawn through the mean static grip forces was approximately parallel to a similar regression line drawn through the mean slip forces.
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loading forces. The onset of the load force was invariably earlier for the high friction surface, and the rate of load force application was greater than the comparable low friction condition. Understandably, the subsequent acceleration, which effectively increases the load force (Flanagan and Wing 1993), was generally much slower for slippery surfaces compared with the adhesive conditions. Although Fig. 2D shows an average of 10 trials, the phenomenon depicted was seen reliably on the majority of individual trials and was observed consistently in all our subjects.

Surface friction continued to affect the ratio of grip to load forces throughout the lifting or loading phase of the task. Figure 2E compares the grip and load force increments for a single smooth surface under a variety of coating conditions. From Fig. 2E, it can be seen that the grip force was greater at any given load force applied to a smooth surface made slipperier by the addition of talc compared with the same surface coated with sucrose.

Both the peak dynamic grip forces and mean static holding forces were exponentially related to the coefficient of friction for all subjects. As might be expected, small decrements in the coefficient of friction of slippery surfaces necessitated large increments in the either the dynamic or static grip force. However, this relationship can be linearized by examining the association of grip forces to the inverse coefficient of friction. The Umea group has attempted to quantify how much the grip force applied by the subject exceeds the minimal force needed to keep an object from slipping. Westling and Johansson (1984) defined the difference between the applied grip force and the slip force as the grasping safety margin. In the present study the safety margin was defined as the mean static grip force during stationary holding measured over the final 500 ms before release minus the grip force at the slip point. Figure 2F compares the mean static grip force with the mean slip force for all subjects with the inverse coefficient of friction of each of the 12 surface conditions. The two linear regression lines, one drawn through the mean grip force and the other through the mean slip force, are nearly parallel, suggesting that the safety margin is approximately constant over this range of friction.

Figure 3A shows the linear correlations between the peak dynamic force and the inverse coefficient of friction for each of the 10 subjects. Peak grip force correlations ranged from 0.67 to 0.96 with a mean of 0.81 (P < 0.01, df = 11). However, when the data from all 10 subjects were pooled, as shown in Fig. 3B, the correlation fell to 0.60 because of the difference between subjects.

DISCUSSION

The results of the present study support the original conclusions of Johansson and Westling (1984a,b; Westling and Johansson 1984) that friction between the skin and a grasped object is a powerful determinant of the grip force used to hold the object against gravity. Furthermore, the results indicate that subjects rely on the friction of the object against
the skin to optimize grip force regardless of whether this friction arises from either the macroscopic surface features in contact with the fingers or the coating between the grasped surface and the skin. However, in spite of this demonstration, the contribution of surface microgeometry to grasp force control cannot be totally excluded until a wider variety of surface textures has been examined. In addition, both the physiological basis for the perception of friction as distinct from roughness and the psychophysical relationship between perceived and real friction are obscure and require further study. It remains to be demonstrated whether subjects use the same mechanoreceptors in scaling for roughness and friction by active touch as they use in isometric grip force control.

The safety margins measured in the present study were \(2.0 - 3.0\) N and were generally greater than those reported by Westling and Johansson (1984), although wide variations in the safety margin between subjects were shown and commented on by Johansson and Westling (1984b). The larger safety margins in the present study are probably due primarily to the greater inherent friction of the armature of the linear motor compared with the free-standing device used by the Umea group. Differences in the instructions to the subjects and in the measurement of the slip point may have contributed as well. The inherent friction of the motor armature would have added 0.4 N to the force needed to lift the object and increased the grip force needed to keep the object from slipping. Despite the fact that friction would not have added to the force needed for stationary holding, it would have added to the perceived load during lifting and possibly biased the safety margin upward. In addition, subjects in the present study were required to maintain a very narrow position window for a relatively short 2-s static holding phase. This compares with the 10- to 15-s holding phase used by Westling and Johansson (1984), which would have given subjects more time to optimize the static grip force by reducing the safety margin. Finally, although the slip point itself was measured from a change in position with a transducer accurate to 0.5 mm, this method may have been less sensitive than the accelerometer used by Johansson and Westling (1984a) and therefore lowered the force level at which slip was detected.

The observation that the force traces for grasping the slippery and sticky surfaces were initially similar until differences appeared in the tangential or lifting forces was unexpected. Moreover, the initiation of the lifting force was earlier for the high friction surface than for the more slippery surface. Conceivably, the amount of slip generated by the tangential load forces on the skin could have provided the information needed to subsequently adjust the grip force to the friction at the skin-surface interface. In contrast, on some trials the rates of grip application for high and low friction diverged immediately, suggesting the anticipation of friction based on immediately prior experience (Johansson and Westling 1984a, 1988a,b; Westling and Johansson 1984).

Obviously, to avoid slip of any given object, the grip force must be commensurate with the load force. However, a corollary of this principal is that in lifting very slippery surfaces where the grip force is close to the maximum, the safety margin is dangerously low, and the object can only be accelerated slowly to avoid slip. An example of this condition is seen in the slower initial displacement of the slippery surface in Fig. 2D.

Friction describes the interaction of two surfaces, and this relationship is not inherently obvious from the surface geometry. Smooth surfaces can demonstrate higher friction than rough ones. Smooth glass, for example, has a higher coefficient of friction against skin than frosted glass. In addition, coatings can interact with surfaces in complex ways. In the present study both the lubricant effect of talc and the adhesive effect of sucrose was greater on the smooth surface than on the textured surfaces. All subjects applied some grip force to the highly adhesive sucrose-coated surface, while in fact, once contact was established, little or no grip force was required at all. The discharge of skin mechanoreceptors to the tangential displacement of surfaces treated with either lubricating and adhesive coatings has yet to be investigated. Also the more general question of how the CNS senses the presence of slippery or sticky coatings on a touched surface has yet to be explained.

In general, skin mechanoreceptors are perhaps more responsive to slip than to tangential strain. Johansson and Westling (1987) reported that both type one and two rapidly adapting receptors (RA I, RA II), and slowly adapting type one receptors (SA I) responded vigorously to slip across the skin. A single 4-μm raised dot, 550 μm diam, which recruited RA I receptors, allowed the subjects to detect relative motion on the skin (LaMotte and Whitehouse 1986; Srinivasan et al. 1990). In contrast, slowly adapting type two (SA II) receptors did not respond to slip but instead responded well to tangential skin strain during stationary holding (Westling and Johansson 1987). This sensitivity of SA IIs to tangential forces and the direction of skin strain is well documented in both glabrous and hairy skin (Edin 1992; Johansson 1978; Knibestol and Vallbo 1970). The ratio of activity in mechanoreceptors responding to slip, to SA IIs responding to the distribution of tangential forces and the direction of adhesive strain on the skin might provide the information needed to generate an estimate of the friction of surfaces in contact with the skin. The generally unpleasant sensations associated with manipulation of sticky or greasy surfaces may be due to the unusually strong or weak tangential force signals to SA IIs, which would ultimately interfere with estimating the frictional properties of manipulated objects.

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Address for reprint requests: A. M. Smith, Centre de Recherche en Sciences Neurologiques, Dept. de Physiologie, Université de Montréal, Case postale 6128, succursale centre ville, Montréal, Quebec H3C 3T8, Canada.

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