Effects of Object Texture on Precontact Movement Time in Human Prehension

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ABSTRACT. Using kinematic data in a precision-grip reaching task, Weir, MacKenzie, Marteniuk, and Cargoe (1991) concluded that prior to contact with an object, its texture does not affect the course of grasping. The present study used their task of reaching for and lifting a slippery-, normal- (polished metal), or rough-surfaced dowel. This occurred under the original, blocked condition, in which textures were held constant within a series of trials, and under a new, randomized condition, in which textures varied randomly from trial to trial. Performance was also examined over more extended periods of practice. Reaction time and precontact movement time were directly measured. In contrast to the results of Weir et al., 1991, reaching for the slippery dowel resulted in slower movement time. This effect was found both early and late in practice for the randomized condition; it was found only in late practice for the blocked condition. These effects can be attributed to the greater geometric and dynamic precision required for lifting a slippery object.

Key words: grasp, movement time, reaching, texture

Grasping is arguably the most fundamental capability of the human hand, one that underlies most of its manipulatory activities. It is not surprising, then, that it has received intense scientific scrutiny, having been analyzed from neurophysiological, behavioral, mechanical, and computational perspectives. Our concern in this study was not only with the act of grasping per se but with preparation and movement prior to contact. In particular, we wished to determine whether these activities become more time-consuming when an object is slippery (i.e., has a low coefficient of friction) and, if so, why.

Weir, MacKenzie, Marteniuk, and Cargoe (1991) previously addressed this question in a study that used kinematic data. They asked subjects to reach for and lift a cylindrical metal dowel that had a surface that was either polished metal (called normal), covered with rough-grit paper (rough), or covered with a lubricant (slippery). (Following Weir and coworkers, we refer here to this variable as texture.) The index-finger-to-thumb aperture and the wrist velocity profiles for the three conditions were very similar in the early stages of reaching. However, compared with the other dowels, trials involving the slippery dowel manifested delays in later stages, so that a longer percentage of the reaching interval occurred after maximum aperture, maximum velocity, and maximum deceleration. Thus the time interval between movement initiation and vertical displacement of the object was longer for the slippery dowel.

The issue of interest was whether these late-stage delays were prior to contact or resulted from actions on the dowel after contact and prior to vertical displacement (pre-liftoff). Weir et al. (1991) did not make use of a contact sensor that would have allowed direct measurement of the point of liftoff. Instead, they used an indirect measure based on kinematic trajectories to address this question. With this measure of precontact movement duration, differences in this variable did not appear to be reliable; only the time interval between contact and liftoff was significantly affected.

Although the null hypothesis with regard to precontact movement time was accepted, we note that if the post-contact times estimated by the Weir et al. (1991) measure are subtracted from the reported movement time, sizable differences are found among the three dowels in precontact time (rough = 604 ms, normal = 632 ms, and slippery = 658 ms). These differences might become statistically reliable if subjects were practiced at the task, which should reduce variability in their movements.

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It would be useful, therefore, to more directly assess the effects of surface properties on precontact movement time, and on the time spent planning the movement (premovement reaction time) as well. Consider that there are two intervals during which a hand might adapt to a low coefficient of friction. One, supported by the results of Weir et al., 1991, is postcontact, after the surface properties have been sensed cutaneously. This form of adaptation was demonstrated in work of Johansson and Westling (1984), who found that subjects who could not see the surfaces of touched objects adjusted their grip force to the coefficient of friction and weight. They also found (1987) that the grip force was adjusted in response to small amounts of slip within 100 ms of contact, providing a mechanism for postcontact accommodation, possibly in the rapidly adapting, low-frequency-sensitive Meissner corpuscles.

It should be noted, however, that the postcontact adaptation described by Johansson and Westling (1984) was reflected in the grip force attained but not the time to reach maximum force, over the range of surfaces investigated. Subjects appeared to adjust the rate of grip-force increase, according to the slipperiness of the object’s surface. (The rate of increase of load force, used for vertical lifting, was unaffected.) Thus subjects achieved different grip-force maxima, but at the same point in time. There is no reason from these data to expect postcontact, preliftoff time to change with slipperiness, as was found by Weir et al., 1991. However, the coefficient of friction even for the most slippery material (silk) used by Johansson and Westling (1984) was undoubtedly greater than that of a lubricated dowel.

The motor performance literature suggests that accommodation to surface characteristics could occur in a second way, prior to contact, if subjects had prior information (e.g., from vision or foreknowledge) of the potential for slip. This makes sense from a computational standpoint as well, for it would be useful to be able to prepare grasp geometry (i.e., finger placement) and force in response to visually apparent object characteristics (see, e.g., Hanafusa & Asada, 1977; Nguyen, 1986; Pollard, 1990).

As will be explained further in the Discussion section, longer preparation (i.e., precontact) times in response to low coefficient of friction could reflect a demand for greater precision in grasp control. In general, precision refers to tolerance for variability in a task. Precision effects in various forms can be seen on both premovement reaction time and precontact arm movement time. For example, the effect of spatial precision on movement time can be seen in Fitts’s law, which shows that at a given distance, smaller targets lead to slower movement (Fitts, 1954). An effect of force precision on movement time was shown by Marteniuk, MacKenzie, Jeannerod, Athènes, and Dugas (1987) in discrete reaching tasks varying in the fragility of the target object (a ball or a light bulb) and the movement goal (placing vs. throwing). With respect to reaction times, Sidaway (1991) found effects of spatial precision (i.e., subtended angle) in a task of reaching to a target. In a task perhaps most relevant to the current interest, Klazky, Fikes, and Pellegrino (in press) found that subjects reaching for an object on a slippery surface, with the requirement that the object not be displaced, took longer both to initiate movements and to execute them. These increases could reflect greater computational complexity involved in planning for and controlling precise movements.

In the present study, we replicated the manipulation of Weir et al. (1991), this time using an apparatus designed to allow the direct measurement of reaction time and precontact movement time. As we mentioned above, the differences between the dowel conditions with respect to precontact movement time that Weir et al. (1991) were unable to show might become reliable if subjects were practiced at the task, reflecting learning and possibly reduced variability. We therefore examined performance over a longer period of trials than had been used by Weir and colleagues. In addition, we examined not only a blocked condition like that used previously but also a comparable series of randomized trials. Randomizing the stimulus should prevent habitual patterns from being carried over from trial to trial.

**Method**

**Subjects**

The subjects were 24 college-age students at the University of California, Santa Barbara. Twelve were assigned to each of the blocked and randomized conditions, which were run consecutively.

**Stimuli**

The stimuli were three aluminum dowels, each 103 mm high by 25 mm diameter and weighing 150 g. A screw was attached to the top of each dowel to facilitate handling by the experimenter. One dowel was lightly polished, a second was covered with black, medium-grade sandpaper (100 grit), and a third was also lightly polished but was covered with a slippery substance. In the blocked condition, this was Vaseline (as had been used by Weir et al., 1991); in the randomized condition, we used K-Y jelly (a water-soluble equivalent, to facilitate clean-up between trials). The slippery dowel in the randomized condition was also painted yellow prior to application of the jelly to better distinguish it visually from the polished dowel. The Vaseline-jelly was renewed periodically during the experiment, approximately every 10 trials or as needed to maintain a sufficiently slippery layer. The slip angle of the dowels when supported by the fingertips was measured to be 51° for the sandpaper, 30° for the normal, and 18° for the slippery (Vaseline). The tangent of this angle is the coefficient of friction (1.22, 0.58, and 0.31, respectively).
Apparatus and Procedure

The apparatus has been described by Fikes, Klatzky, Pellegroino, Hebert, and Murdock (1990). The subject sat in front of a liquid-crystal shutter, with the thumb and index fingers of the right hand opposing one another and resting on a microswitch; the remaining fingers were folded into the palm. The experimenter placed a dowel on a pad equipped with a piezoelectric contact sensor. The shutter, microswitch, and contact sensor were interfaced to an IBM PC/AT compatible computer via the parallel I/O port. After placement of the dowel, the experimenter’s key press on the computer keyboard initiated a beep, informing the subject the trial was beginning. After 500–1,000 ms (randomly determined with a uniform distribution), the shutter opened and the dowel was exposed. The subject was instructed (as in Weir et al., 1991) to move as quickly and as accurately as possible. He or she was to use only the thumb and index finger to pick up the dowel and to hold it away from the supporting surface until a signal from the experimenter, who then took it from the subject’s hand. Reaction time was defined as the time between object exposure and release of the microswitch, and movement time was defined from release of the switch up to the point of contact with the dowel.

In the blocked condition, each subject took part in two periods with each dowel. The three dowels were rotated over periods twice in the same order; a Latin square design was used to assign six orders across subjects. The first period for each dowel had 20 experimental trials each (the number of recorded trials in Weir et al., 1991), and the second period for each dowel had 30 experimental trials. One catch trial was given for every 10 trials within each period; in this case, no dowel was presented and the subject was not to initiate movement.

In the randomized condition, each subject took part in two periods. Each contained three series of 21 experimental trials each (7 trials per object) and 2 catch trials. The dowels occurred in random order within each series. The subject wiped the hand on a moist towel after contact with the slippery dowel.

Results

Data from the blocked and randomized conditions were analyzed separately. For each condition, an omnibus $3 \times 2$ (Texture $\times$ Period) analysis of variance (ANOVA), with repeated measures on both factors, was used with each dependent variable (movement time and reaction time). Each analysis used individual-subject means computed across all trials within a texture-period condition for a given subject.

Blocked Condition

Means across subjects for movement times and reaction times are shown in Figure 1. The omnibus $3 \times 2$ ANOVA of movement time showed marginal effects of texture, $F(2, 22) = 2.73, p = .08$; and period, $F(1, 11) = 3.64, p = .09$; for the interaction, $F(2, 22) < 1$. As was explained earlier, we incorporated two periods in the design, one essentially equivalent to the amount of practice used by Weir et al., 1991 (20 trials), and the second (30 trials) to investigate effects with a higher level of practice. Simple effects tests were therefore run within each period, by performing one-way repeated ANOVAs over the texture conditions. In support of Weir and coworkers’ findings, the effect of dowel texture on movement time in the first period was not significant, $F(2, 22) < 1$. Because the Weir et al., 1991, study discarded the first five trials of their subjects, the present analysis was repeated after eliminating the first five trials of each dowel texture, and there was again no effect of texture, $F(2, 22) < 1$.

In contrast, the same one-way ANOVA on movement time in the second period showed a significant effect of texture, $F(2, 22) = 7.18, p < .05$. Single-degree-of-freedom comparisons were used to further assess the locus of this effect. Because the principal effects in Weir et al., 1991, had been obtained with the slippery dowel, we compared the mean for that dowel with the mean
of the others. This effect was significant, $F(1, 11) = 6.76$, $p < .05$. The mean for the rough dowel was also compared with that of the normal, showing a slower movement time for the rough texture, $F(1, 11) = 8.63$, $p < .05$. A nonindependent contrast comparing the rough and slippery dowels failed to reach significance, $F(1, 11) = 2.20$, $p > .15$.

An omnibus $3 \times 2$ ANOVA on reaction time showed a significant effect only of period, the second being faster than the first, $F(1, 11) = 11.42$, $p < .01$. Neither the effect of texture, $F(2, 22) < 1$, nor the interaction, $F(2, 22) = 1.23$, $p > .25$, were significant. Simple effects tests of texture at each level of period also were nonsignificant, both $Fs(2, 22) < 1$.

**Randomized Condition**

Recall that this condition constituted two periods, each comprising three series of trials; in each series, the three textures occurred seven times in random order. Thus the number of trials in each period was comparable with that in the first period of the blocked condition. Means for movement time and reaction time are shown in Figure 2. An omnibus $3 \times 2$ ANOVA on movement time revealed a significant main effect of texture, $F(2, 22) = 9.64$, $p < .01$, but nonsignificant effects for both period, $F(1, 11) = 1.70$, $p < .25$, and the interaction, $F(2, 22) < 1$.

As in the blocked condition, simple effects of texture for each period were assessed using separate one-way repeated-measures ANOVAs. In the first half of the condition (Period 1), the effect of texture on movement time was significant, $F(2, 22) = 5.64$, $p < .05$. Planned comparisons revealed that the mean of trials with the slippery dowel was slower than the mean of the others, $F(1, 11) = 7.40$, $p < .05$, which did not differ from one another, $F(1, 11) = 1.01$, $p > .25$. We noted that if the first five trials of each texture were deleted from the analysis, the effect of texture still reached significance, $F(2, 22) = 3.93$, $p < .05$. In the second half (Period 2), the movement time effects were similar. The effect of texture was significant, $F(2, 22) = 9.36$, $p < .01$; the mean for the slippery dowel was significantly slower than the mean for the others, $F(1, 11) = 11.27$, $p < .01$; and the rough and normal did not differ, $F(1, 11) = 1.37$, $p > .25$.

As in the blocked condition, the omnibus $3 \times 2$ ANOVA on reaction time showed only an effect of period, $F(1, 11) = 12.73$, $p < .01$, with the second period again being faster than the first. Neither texture, $F(2, 22) = 2.23$, $p > .10$, nor the interaction, $F(2, 22) < 1$, reached significance. Simple effects tests of texture also showed no significant effects at either period, $Fs(2, 22) < 1.32$ and $1.40$, both $ps > .25$.

**Comparison Between Conditions**

For reasons explained below, the two conditions (blocked and randomized) were compared with respect to the overall mean reaction times and movement times (collapsed over texture and period). The randomized condition averaged 27 ms slower reaction time than the blocked, but this difference did not reach significance (between-subject $t[22] = 1.29$, $p > .10$). There was virtually no difference in movement times between the two conditions ($11$ ms, $t[22] = .15$, $p > .25$).

**Discussion**

To summarize our results, there is clear evidence that reaching for a slippery dowel results in slower movement time prior to contact. This effect was found both early and late in practice for a randomized condition in which dowel surfaces were intermixed from trial to trial. It was found only late in practice when dowel surfaces were blocked (in which case the rough dowel was also relatively slow to be reached). The low levels of practice and the blocked trials of Weir et al. (1991) may explain why reliable effects were not obtained in that study, although their data similarly showed a trend toward slow precontact movement time for the slippery dowel. Premovement reaction time showed no differences among the dowels; apparently, advance planning for simple grasping takes no longer for a slippery surface than a rough one.
The data of Weir et al. (1991), along with findings of Johansson and Westling (1984), show clearly that haptically cued characteristics of an object’s surface have temporal and dynamic consequences subsequent to contact. Slowed lifting of a slippery object appears to reflect additional time needed to apply adequate grip force, which would be necessary to compensate for the reduced coefficient of friction (see below). In contrast to the conclusion of Weir et al., the present data further indicate that visually cued, but haptically relevant, characteristics of objects can have temporal consequences prior to contact as well.

In the paragraphs that follow, we make the argument that the slowing of precontact movement time with a slippery object reflects anticipation of constraints on the geometry of the grasp and the dynamics of grasping and lifting. These constraints increase for a slippery object because of the lower tolerance for error, and the resulting increased demands for precision may translate into effects on movement kinematics.

To develop this argument, it is necessary to consider the process of achieving a stable grasp. This process has been analyzed for planar objects by Fearing (1986), in the context of robotic grasping. Fearing assumed that friction was present and that the object was planar, in which case only two fingers were necessary. (In the frictionless situation, four fingers would be needed; see Lakshminarayana, 1978.)

According to Fearing, 1986, there are three requirements for achieving a stable grasp by the two fingers: First, the grasped object must be in equilibrium. This means that the forces exerted by the fingers must be collinear (i.e., the directions of the two forces must meet on a direct line between the fingers), equal, and opposite in sign (i.e., in opposing directions).

Second, to prevent slip at the fingers, all forces must lie within what is called the cone of friction. As Figure 3 indicates, the force applied by the finger at the surface of an object can be decomposed into two orthogonal components, one normal to the surface and the other tangential (\( F_n \) and \( F_t \), respectively). The cone of friction is defined by an angle, \( \alpha \), on each side of the normal force component. This is the angle of friction, which has as its tangent the coefficient of friction (\( \mu \)) of the object surface (i.e., \( \alpha = \tan^{-1} \mu \)). The force applied by the finger (i.e., the vector sum of the normal and tangential components) must lie within the cone of friction. That is, where \( \varphi \) is the angle of the applied force relative to the surface normal (i.e., \( \varphi = \tan^{-1} \left| \frac{F_t}{F_n} \right| \)), \( \varphi \) must be less than \( \alpha \).

Thus Equation 1 must hold:

\[
\tan^{-1} \left| \frac{F_t}{F_n} \right| < \tan^{-1} \mu, \text{ so that } \mu \cdot F_n > |F_t| \quad (1)
\]

If the normal component is not large enough, the force will lie outside of the cone and the finger will slide in the tangential direction.

Extending this analysis to two opposing fingers, Fearing (1986) showed that the angle between their surface normals must be less than twice the angle of friction. This has implications for the consequences of finger placement, that is, grasp geometry, as explained below.

The third requirement is that it should be possible to increase the grasping force to prevent movement when another, disturbing force is applied. Lifting a dowel vertically generates a disturbing force tangential to the grasped surface. Given this increased tangential force, one must increase the minimum normal force to maintain the grasp within the cone of friction (see Equation 1). Westling and Johansson (1984) clearly demonstrated the time course of increased grasping force as an object is lifted. The change in grip force occurred in parallel with the change in the vertical load force, thus keeping the resultant force within the cone of friction.

A dowel can be analyzed as a planar object by considering either a horizontal projection to the picture plane, forming a circle, or a vertical projection, forming a rectangle. First consider the circular projection. As shown in Figure 4, if the fingers are misplaced so that they do not oppose through the center (i.e., the fingertips are too close to the edge of the dowel), their surface normals will have some angle greater than zero between them. Recall that this angle must be less than twice the angle of friction. Thus a low coefficient of friction allows little geometric tolerance: If the normal components of the two finger forces do not oppose virtually perfectly, the object may squirt from the fingers. One way to reduce this problem is to contact the dowel surface with more than two fingerpads. Seen as a horizontal projection, this might constitute a scenario with more than two fingers that could adequately be handled by a frictionless grasp (Lakshminarayana, 1978; Trinkle, Abel, & Paul, 1987).

Next consider placement of the fingers relative to the vertical, rectangular projection. A person may be able to compensate for vertical misalignment with what Fearing (1986) called a “hand priority grasp.” Following earlier
work by Mason (1985), Fearing suggested that grasping an object can generally take this form, which uses slip at the fingers and allows the object to move so a stable position can be established after contact. This constitutes a general algorithm for grasping, using tactile feedback, without need for vision. At each finger, the object may slip or roll; slipping occurs when the finger force is outside the cone of friction, and rolling when it is within the cone of friction and there is a moment about the finger. An alternative to hand priority is “object priority grasping,” where the fingers are allowed to slip but the object remains stationary.

Figure 5 illustrates hand priority grasping for a rectangular projection of the dowel when the two fingers imperfectly line up along the vertical. When applied, the forces are assumed to be collinear but not normal to the surface, because of the misalignment. Because the forces are outside of the cone of friction, the two fingers slip toward one another and their forces become increasingly normal, ultimately moving into the cone of friction. In addition, moments produced by the fingers result in rotation of the dowel. The case shown is one where rotation and slip ultimately produce a stable grasp. However, an object with a lower coefficient of friction could slip from between the fingers or spin out of the grasp.

Fearing’s (1986) definitions of both hand and object priority grasping present postcontact scenarios for achieving a stable grasp. There is no requirement for adjustment prior to contact. This reflects Fearing’s concern with a situation in which there is no prior model of the object, as would be obtained with vision; nor does the model assume visually guided reaching. An important question is what would be gained from precontact preparation for an object, particularly one with a low coefficient of friction.

In answer, the above analysis suggests two types of problems for achieving a stable grasp and lifting an object: geometric, that is, pertaining to placement of the fingers in relation to each other and the object surfaces, and dynamic, relating to disturbing effects of gravity and the need for adequate normal force to compensate for tangential forces (including those of gravity). It is important to emphasize that the lower the coefficient of friction, the lower the tolerance of the system for error.

Precontact preparation might help to deal with both types of problems. We note first that our data indicate that such preparation occurs during movement, not before it, and thus must affect movement kinematics. With respect to geometric problems, one possibility is that people prepare finger placement more carefully when they know that an object is slippery. With respect to dynamic problems, possibly it takes longer to prepare to exert the stronger normal force required to stay within the cone of friction of a slippery object (see Carlton, Carlton, & Newell, 1987, for an isometric equivalent). (Geometric and dynamic factors may interact, in that a strong normal force is undesirable if the fingers are not...
adequately placed.) Yet another possibility is that the need to control counter-gravitational acceleration during lifting, to avoid undue tangential forces, leads to slower preparation for contact. This could reflect, for example, the desire to completely brake the reaching movement of the arm before lifting. The present analysis provides an estimate of the slowing for the total arm/hand trajectory caused by these geometric and dynamic effects. A kinematic analysis would be useful to localize the slowing in the transport trajectory and potentially to identify concomitant adjustments in the grasp trajectory, such as slowed grasp formation and discontinuities, which might particularly occur if the finger configuration was visually guided and the feedback loop was reasonably slow (see Wing, Turton, & Fraser, 1986, for related effects).

One way to summarize these effects is that a lower coefficient of friction imposes lower tolerance for error and increases the precision demands of a grasping task. As was noted above, effects of precision on movement time have been found in a variety of other contexts in the motor behavior literature. The present article indicates that similar effects are obtained when precision demands are imposed by an object’s surface properties and are communicated in advance of movement. A low friction coefficient need not reflect intrinsic properties of the object’s surface alone; it could also reflect slipperiness of the hand surface. Thus a further test of our ideas would be to measure precontact movement time when the hand has been lubricated. It would also be of interest to extend these results to conditions in which subjects were not required to move rapidly, unlike the subjects studied here and those of Weir et al., 1991.

We cannot be certain why movement-time differences between the blocked and randomized trials of the rough dowel were obtained in the present studies. There are two obvious differences between the blocked and randomized conditions; however, these would be likely to increase reaction time—not movement time—for the randomized condition. One difference is the need to identify the dowel when presentations are randomized but not when they are blocked. The second difference derives from the suggestion by Johansson (1991) that reaching and grasping incorporate a preplanning process, during which appropriate motor program parameters are set, based on sensorimotor memories representing relevant object properties. When a sequence of grasped objects is randomized, these parameters must be reset anew from trial to trial; this is not the case for the blocked condition. Despite these differences, however, the small difference in reaction time between the randomized and blocked conditions was not significant.

It could be argued that in everyday activities, it is more common to grasp a variety of objects about which something is known than to repetitively grasp a single object that is relatively unfamiliar. On this basis, the practiced, randomized condition would be preferable for assessing
effects of texture on precontact time. It is this condition that shows such effects most clearly in the present data.

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NOTE

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REFERENCES


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