Control of Grasp Stability When Humans Lift Objects With Different Surface Curvatures

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Jenmalm, Per, Antony W. Goodwin, and Roland S. Johansson. Control of grasp stability when humans lift objects with different surface curvatures. J. Neurophysiol. 79: 1643–1652, 1998. In previous investigations of the control of grasp stability, humans manipulated test objects with flat grasp surfaces. The surfaces of most objects that we handle in everyday activities, however, are curved. In the present study, we examined the influence of surface curvature on the fingertip forces used when humans lifted and held objects of various weights. Subjects grasped the test object between the thumb and the index finger. The matching pair of grasped surfaces were spherically curved with one of six different curvatures (concave with radius 20 or 40 mm; flat; convex with radius 20, 10, or 5 mm) and the object had one of five different weights ranging from 168 to 705 g. The grip force used by subjects (force along the axis between the 2 grasped surfaces) increased with increasing weight of the object but was modified inconsistently and incompletely by surface curvature. Similarly, the duration and rate of force generation, when the grip and load forces increased isometrically in the load phase before object lift-off, were not influenced by surface curvature. In contrast, surface curvature did affect the minimum grip forces required to prevent frictional slips (the slip force). The slip force was smaller for larger curvatures (both concave and convex) than for flatter surfaces. Therefore the force safety margin against slips (difference between the employed grip force and the slip force) was higher for the higher curvatures. We conclude that surface curvature has little influence on grip force regulation during this type of manipulation; the moderate changes in slip force resulting from changes in curvature are not fully compensated for by changes in grip force.

INTRODUCTION

When humans lift and manipulate objects, they apply grip forces that are large enough to prevent the object from slipping but avoid using excessive grip forces that may damage the object or the hand or cause unnecessary muscle fatigue. Grasp stability is achieved by automatically increasing or decreasing grip forces (normal to the grasp surfaces) in parallel with increases or decreases in the load forces (tangential to the grasp surfaces) (Johansson and Westling 1984a; Westling and Johansson 1984). This coordinated pattern of forces has been reported for a number of grasp configurations in various manipulative tasks where grasp stability is essential (e.g., Burstedt et al. 1997a,b; Cole and Abbs 1988; Flanagan and Tresilian 1994; Flanagan and Wing 1993, 1997; Johansson et al. 1992a,b; Jones and Hunter 1992; Kinoshita et al. 1996). The magnitudes of the fingertip forces and the coordination between the grip forces and the load forces, which depend on the physical properties of the manipulated object, are determined largely by anticipation before commencement of the task, based on previous experience with similar objects (Edin et al. 1992; Flanagan and Wing 1997; Jenmalm and Johansson 1997; Johansson and Westling 1984a, 1988). Recall of the relevant stored memories can be triggered by either visual or haptic sensory information (Gordon et al. 1991, 1993; Jenmalm and Johansson 1997). Whenever necessary, the putative internal models of the object at hand can be updated rapidly as a result of somatosensory afferent information reflecting specific mechanical events at the digit-object interface. This has been shown to apply to models that depend on the object’s shape (Jenmalm and Johansson 1997), the frictional characteristics at the digit-object interface (Edin et al. 1992; Johansson and Westling 1984a), and the weight of the object (Gordon et al. 1993; Johansson and Westling 1988).

These finding all are based on studies in which the manipulated objects had flat grasp surfaces. In everyday activities, however, the surfaces of most objects that we handle are curved. Psychophysical studies have shown that humans are remarkably good at discriminating curved surface profiles during active haptic exploration (Davidson and Whitson 1974; Gordon and Morison 1982; Kappers et al. 1994) as well as in passive tasks where the objects are applied to the fingertips (Goodwin et al. 1991; Srinivasan and LaMotte 1987). Sensory information related to surface curvature is conveyed to the brain by populations of cutaneous afferents from the glabrous skin (Goodwin et al. 1995, 1997; LaMotte and Srinivasan 1987a,b, 1996). Microneurography studies in humans have shown that signals from digital mechanoreceptors also carry information that is crucial for maintaining grasp stability during manipulation (Johansson and Westling 1987; Macefield et al. 1996; Westling and Johansson 1987). These signals allow us to adjust the ratio between grip and load forces automatically so that an adequate safety margin against frictional slips is maintained despite differences in frictional conditions at the digit-object interface (Cadoret and Smith 1996; Cole and Johansson 1993; Edin et al. 1992; Flanagan and Wing 1995; Forssberg et al. 1995; Häger-Ross et al. 1996; Johansson and Westling 1984a; Westling and Johansson 1984). Such automatic adjustments also occur when lifting objects with grasp surfaces that are not parallel but are tapered (Jenmalm and Johansson 1997). However, it is not known how the curvatures of an object’s surface influence the control of grasp stability.

In the present study, we examined the effect of surface curvature on the fingertip forces used by humans when lifting and holding objects of various weights. Specifically, we ana-
lyzed the extent to which surface curvature influenced the critical grip-to-load force ratio at which frictional slip occurred, and determined whether such influences were reflected in the grip-to-load force ratio used by the subjects.

**METHODS**

**Subjects and general procedure**

Experiments were performed on eight right-handed healthy human volunteers (3 females and 5 males) ranging in age from 24 to 53 yr. All gave their informed consent, and the experimental protocol was approved by the local ethics committee. About 5 min before the experiments, the subjects washed their hands with soap and water. During the experiments they sat in an office chair with the right upper arm parallel to the trunk and the elbow resting either on the right arm of the chair or on their right thigh. They were asked to lift a test object, located ~10 cm distal to the hand, by using the pads of the right thumb and index finger. The object, which was positioned on a table, was lifted vertically 1–2 cm with a movement consisting mainly of flexion of the elbow after a 10-cm reach. The subjects could see the object and their digits throughout the experiment.

**Apparatus**

The base of the test object, illustrated in Fig. 1A, contained a slot in which different weights could be inserted and easily changed between trials. The total weight of the object could have one of five values, 168, 252, 331, 465, and 705 g, which corresponded to static vertical lift forces of 1.65, 2.48, 3.25, 4.56, and 6.92 N, respectively. The object’s center of gravity varied somewhat with the different weights but was always well below the center of the grasped surfaces. Six pairs of exchangeable, matching, spherically curved surfaces were used (Fig. 1B). Two were concave with radii of 20 or 40 mm, one was flat, and three were convex with radii of 20, 10, or 5 mm. The corresponding curvatures of the six pairs, given by the reciprocal of the radii, were 0.50, 0.25, 0 (flat surface), 50, 100, and 200 m⁻¹, respectively. All surfaces were coated with silicon carbide grains (50–100 μm) that were attached with adhesive and then coated with a thin layer of cyanoacrylate. When attached to the object, the most lateral parts of the grasp surfaces were separated by 59 mm.

Each grasp surface was attached to the test object via a six-axis force-torque sensor (Nano F/T transducer, ATI Industrial Automation, Garner, NC) that measured the forces and torques in three dimensions. The three force components were defined as follows. Grip force was measured along an axis parallel to a line passing through the centers of the opposing grasp surfaces. Two force components were measured tangential to this axis, one oriented along the object’s vertical and the other in a direction normal to this component. The vector sum of the two components constituted the load force, which essentially was accounted for by the vertically directed lift force generated by the subject. Grip forces were measured with a resolution of 0.05 N and tangential forces with a resolution of 0.025 N. The three torques were mea-

**Fig. 1.** Instrumented test object, surface curvatures and measurements taken for analysis. A: test object equipped with a pair of matching curved surfaces (curvature 50 m⁻¹ illustrated). Different weights were inserted in a slot in the base of the object to change its mass; e.g., object’s center of gravity. B: lateral view of the 6 different pairs of spherical surface curvatures. Grasp areas are indicated: ——, convex and flat surfaces; · · ·, concave surfaces. C: signals shown as a function of time during different phases of a single trial (weight = 465 g, surface curvature = 50 m⁻¹). Grip forces, load forces and their ratio are shown for the index finger (—) and the thumb (···), plus the vertical position of the object and its sideways tilt angle. Interval a indicates the load phase. ←, different points at which grip force was measured, i.e., when the sum of the load forces was 10, 50, and 90%, of the total static load force (LF) and the maximum grip force. Interval b shows the time period, extending from 3 to 4 s after the object initially was touched, when static hold phase measurements were taken. Sound indicates the command given to the subject to slowly decrease the grip force until the object slipped and was dropped. D: slip test indicated by the hatched rectangle in C shown on an expanded time scale. Slip ratios measured for each digit are indicated (·).
measured around the three orthogonal force axes when intersecting at the center of the grasp surface. The torque sensing range was ±250 mNm, with a 0.125-mNm resolution. An electromagnetic position sensor (FASTRAK, Polhemus, Colchester, VT) was used to measure the vertical position of the object (resolution: 0.12 mm) and its angle of tilt in relation to the vertical (resolution: 0.025°).

Lifting task

There were 30 curvature-weight combinations (6 curvatures × 5 weights). Each lift series was divided into six blocks consisting of five consecutive trials during which the surface curvature was held constant, and the five different weights were presented in an unpredictable order. The surface curvature was changed between the six blocks, such that each of the six curvatures was presented once in each series. All subjects performed three lift series that differed from each other both with regard to the sequence of presentation of the blocks of curvatures and with regard to the sequence of weights within each block. Furthermore, the order of presentation was randomized across subjects. In total, each subject thus performed 90 trials representing 3 trials at each curvature-weight combination.

Subjects were instructed to grasp the surfaces at their centers and to lift the object vertically through a few centimeters, avoiding any tilt, and to hold it steady. To estimate the critical grip-to-load force ratio at which slips would occur, each trial was terminated by the subject slowly spacing the engaged digits until the object was dropped (Johansson and Westling 1984a). The subject’s cue to start this “slip test” was a 1-kHz sound signal, lasting 0.1 s, which occurred 5 s after the object initially was touched (defined as the time at which the sum of the grip forces at the two grasp surfaces first exceeded 0.3 N).

The total duration of each trial, including the slip test, was 6–10 s. Before data collection, the center of one convex and one concave surface carefully was pointed out to the subject, and the lifting task was demonstrated by the experimenter. The subject then performed five practice trials using the flat grasp surfaces and an object weight of 331 g. None of the subjects ever dropped the object accidentally.

Data collection and analysis

A flexible data acquisition and analysis system (SC/ZOOM, Department of Physiology, Umeå University) was used to sample signals from the force-torque sensors (400 samples/s; 12-bit resolution) and the position-angle sensor (120 samples/s; 14-bit resolution).

STATIC GRIP AND LOAD FORCES. Grip and load forces were measured independently for the thumb and the index finger. For each trial, the static grip and load forces were calculated as the summed load forces at the two grasp surfaces (

\[ F_{\text{grip}} = F_{\text{load}} \]

and angle at the onsets of the first and second slips. Thus the angle between the grasp surface and the digit did not change appreciably, and the grasp geometry during the static phase was representative not only of the grasp geometry at the point of first slip but also at the point of second slip. For each digit, we measured the grip force and the load force at the instant when slip commenced and computed the critical grip-to-load force ratio termed the slip ratio. The minimum static grip force required to prevent slip, termed the slip force, was estimated for each digit as the product of the slip ratio and the static load force. The safety margin was calculated as the difference between the static grip force and the slip force expressed as a fraction of the static grip force.

GRASP POINTS. Subjects were asked to grasp the surfaces at their centers using their fingertips, and there were no gross deviations visible to the experimenters. However, there would have been some variation in the grasp points, and we expected most variation to occur with the flat surfaces because these provided more grasp options then the curved surfaces. For a flat surface, it is possible to compute the equivalent single point of grip force attack from the torque and force measurements as described previously (Kinoshita et al. 1997). Subjects grasped the flat surfaces remarkably close to their centers. During the static phase, the deviation from the center point in the horizontal direction was 0.6 ± 1.8 mm for the thumb and 0.5 ± 2.2 mm for the index finger (data from all trials pooled). In the vertical direction, the deviation was 1.6 ± 1.8 mm for thumb and 1.5 ± 2.3 mm for the index finger, indicating that on average they grasped slightly above the center points. However, there was no systematic difference in the vertical position of the grasp points for the two digits which could have contributed to an asymmetric load distribution; the mean value for the vertical asymmetry of the grasp points was 0.05 ± 2 mm (data pooled across subjects).

TORSIONAL LOADS. It has been shown that the presence of torsional loads has an effect on the slip forces and grip forces (Kinoshita et al. 1997). In our experiments, such loads could have resulted from the object tilting about the grip axis, i.e., a line joining the points of grip force application at the grasp points. Such torques were estimated for the flat surfaces by taking into account the location of the actual points of force application as described earlier. In addition, they were estimated for the most curved surfaces (200 m−1) by direct measurement from the transducers, assuming that the equivalent single point of fingertip force would be centered on the sharp curvature. For the flat and maximally curved surfaces the estimated torques were merely 4.1 ± 3.5 and 2.1 ± 1.5 mNm, respectively (means ± SD of absolute values; data from all trials and both grasp surfaces pooled). Torques of these magnitudes represent only small torsional loads with marginal effects on the slip forces and grip forces (Kinoshita et al. 1997).

STATISTICAL ANALYSIS. Repeated measures analyses of variance (ANOVAs) were used to evaluate the influence of object weight (168, 252, 331, 465, and 705 g), surface curvature (−50, −25, 0, 50, 100, and 200 m−1) and digit (thumb and index finger) on the following measures: static grip force, static load force, slip ratio, slip force, safety margin, maximum grip force, and grip force when the load force sum was 10, 50, and 90% of the total static load force. Repeated measures ANOVAs also were used to evaluate the influence of the object’s weight and of the curvature of the surfaces on the load phase duration and on the peak rate of grip force increase during the load phase. Pearson product-moment cor-

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relations were used to evaluate correlation between employed grip-to-load force ratios and corresponding slip ratios for each digit as described in RESULTS. The level of probability selected as statistically significant for the correlations was \( P < 0.05 \); all reported positive correlation coefficients were significant. Values reported in the text for data pooled across trials for all subjects refer to means \( \pm \) SD. In many figures, subject means \( \pm \) SE (\( n = 8 \)) are presented. For each subject, and for each of the 30 stimulus combinations, values for the three trials were averaged and the subject SE, \( n = 8 \), was calculated for these average trials. The average trials also were used in the ANOVA analyses.

RESULTS

The present results deal with three main points. The first concerns the manner in which the minimum grip force to prevent frictional slips, termed slip force, depends on surface curvature and digit load. The second point addresses how subjects regulate the employed grip forces to obtain grasp stability when holding an object stationary in air under various combinations of surface curvature and load force. The final point concerns possible influences of surface curvature on the coordination of the grip and load forces in the load phase, when these forces increase isometrically before object lift-off.

Minimum grip forces to prevent frictional slips during static hold phase

The slip force during the static hold phase was estimated, for each digit and each trial, as the product of the measured slip ratio and the static load force.

SLIP RATIO. The critical grip-to-load force ratios at which frictional slip occurred during the slip test (slip ratios) was measured independently for the thumb and the index finger. The behavior, shown in Fig. 2, was similar for the two digits. For data averaged across subjects, the slip ratio was maximum at a surface curvature of either 0 or 50 m\(^{-1}\), depending on the weight of the object, and decreased for more convex surfaces and for concave surfaces. For example, with a weight of 331 g, the slip ratio of the index finger for the most convex surface (curvature 200 m\(^{-1}\)) was on average 71% of that for the flat surface (0 m\(^{-1}\)). The corresponding value for the most concave surface (\(-50\) m\(^{-1}\)) was 58%.

The surface material used by us had more stable frictional characteristics than many other materials that have been investigated (cf. Johansson and Westling 1984b; Smith and Scott 1996). Nevertheless, there was some variation between subjects in the effects of surface curvature on slip ratios. This is shown in Fig. 2C, where slip ratios for the index fingers of individual subjects have been averaged across the five object weights. A second aspect of variable frictional characteristics is evident in the modest increase in slip ratios with an increase in the weight of the object. This effect was greater for the more convex surfaces and was more pronounced for the thumb than for the index finger. ANOVA showed a significant effect on slip ratios for the curvature of the surfaces (\( P < 0.001 \)) and for the weight of the object (\( P < 0.001 \)) with a significant interaction between curvature, weight, and digit (\( P < 0.03 \)). There was no significant effect for the digit (thumb or index finger).

STATIC LOAD FORCE. Needless to say, during the static hold phase, load forces increased substantially with an increase in the weight of the object (Fig. 3A). However, the load force taken up by the two digits was different (\( P < 0.02 \)), with the index finger taking a higher proportion of the total load. The load on the index finger exceeded that on the thumb in 76% of the trials and, averaged across all subjects and trials, the ratio of these two forces was 1.09 \( \pm \) 0.15. This asymmetry of load force distribution was not affected by surface curvature. It resulted mainly from the subject’s tendency to tilt the object sideways in a direction corresponding to slight pronation. The measured tilt angle was, on the average, 1.59 \( \pm \) 0.95°, which was too small to be noticed by the experimenters during visual inspection of the subject’s performance. Load force differences calculated from the
Relationships between static grip forces and minimum grip forces to prevent frictional slips

Figure 3C shows the grip forces that subjects employed during the static hold phase. Grip forces increased substantially with an increase in the weight of the object \((P < 0.001)\) but were not affected significantly by the curvature of the surfaces \((P > 0.14)\). Because of the tilt of the object as considered earlier, the grip force was, on average, slightly greater for the thumb than for the index finger \((P < 0.001, \text{main effect by digit on grip force})\). As expected from the mechanics of the setup, linear regression between the measured tilt angle and a tilt angle computed from the differences in grip forces showed close agreement \((\text{slope } = 1.04, r = 0.87)\).

Slip forces in Fig. 3B varied significantly with surface curvature but grip forces in Fig. 3C did not. Thus for our subjects as a group, the variation in slip force with surface curvature was not reflected robustly in the grip force used. However, as illustrated in Fig. 4, A–D, for individual subjects there was some variation of grip force corresponding to changes in slip force produced by changes in surface curvature. Static grip forces and corresponding slip forces shown for the index finger of four separate subjects lifting the 331-g weight illustrate the variability between individuals. Adjustment of the grip force with changes in the slip force appear to be more robust for the flat and convex surfaces than for the concave surfaces. With concave surfaces, the slip force could decrease substantially without much decrease in the corresponding grip force (e.g., Fig. 4, B–D).

The extent of the adjustment of grip force in each subject was analyzed further by correlating the employed grip-to-load force ratio with the slip ratio over all trials \((\text{Fig. 4, E–H})\). For six of our eight subjects, the correlation between these two variables was positive, indicating that these subjects adjusted to the changes in slip ratio. The correlation coefficients ranged from 0.29 to 0.80 \((\text{mean } = 0.47)\) for data from the index finger, and similar results were obtained for the thumb \((\text{coefficients: } 0.25–0.62)\). Figure 4, E–G, shows data from three subjects where correlation was positive, and Fig. 4H shows data from one subject where correlation was not positive. For subjects showing a positive correlation, even though the intertrial variability was considerable, the magnitude of the adjustment as judged from the slope of the regression line was substantial but far from complete. The slopes had values between 0.34 and 0.89, i.e., the slip ratio change was compensated for on the average by 34–89% of that required for a full compensation \((\text{slope } = 1)\).

Safety margin against frictional slips during the static hold phase

The safety margin against frictional slips was defined as the difference between the employed static grip force and the slip force, expressed as a fraction of the static grip force. As seen in Fig. 3, grip forces were generally lower for the index finger than for the thumb, and slip forces were generally higher. As a consequence, in most trials (65%) the index finger had a smaller safety margin than the thumb. Also, during the slip test, the first slip occurred at the index finger.
FIG. 4. Adjustment of grip force to changes in slip ratios. A–D: static grip forces and corresponding slip forces measured at the index finger for 4 different subjects lifting the 331-g weight. ● and ○, grip forces and slip forces, respectively, in all 3 trials, and the curves represent the corresponding mean values. □, absolute safety margin, measured here by the excess in grip force used to prevent slip (mean data). E–H: employed grip-to-load force ratio plotted against slip ratio for the same subjects and digit as in A–D. Symbols show all 90 single trials, and the line shows the linear regression. Correlation coefficient was significant for subjects 2–4 (P < 0.001) for whom the slope of the linear regression was 0.57, 0.54, and 0.66, respectively.

in the majority of trials (68%). Because the grasp became unstable at the first slip and because the safety margin was different for the two digits (P < 0.01), grasp stability was analyzed using data from individual trials taken from the digit that showed the smallest safety margin (Fig. 5); the safety margin of the accompanying digit was some 25% larger. The safety margin in Fig. 5 clearly was influenced by the surface curvature (P < 0.001), being higher for the most convex and concave curvatures than for the flatter surfaces. The nonconstant safety margin again verifies that the changes in employed grip force did not fully match the changes in slip force as the curvature of the surfaces changed. The safety margin also was influenced by object weight (P < 0.001), increasing with lighter objects as observed previously (Westling and Johansson 1984).

Development of fingertip forces during the load phase

Figure 6A shows the temporal development of the grip and load forces during the initial phase of trials for one subject lifting the 331-g weight. Forces averaged for the two digits are shown for three single trials from one lift series in which the surface curvature was –50, 0, and 200 m⁻¹, respectively. From this panel and Fig. 6B, it can be seen that, regardless of surface curvature, the grip and load forces increased in parallel during the load phase as has been described previously for lifts with flat grasp surfaces (Johansson and Westling 1984a).

Previous studies with flat grasp surfaces have shown that both the duration of the load phase and the rate of force development in the load phase increase with an increase in the weight of the object (Gordon et al. 1993; Johansson and Westling 1988). We analyzed, as a function of surface curvature and of weight, the duration of the load phase (as a measure of the average rate of load force increase), shown in Fig. 6C, and the peak rate of grip force increase (not illustrated). Surface curvature did not influence either of these measures (P > 0.21 in both instances) but, as for previous studies with flat surfaces, the weight of the object influenced both measures (P < 0.001).

In a previous section we examined, for the static phase, the effect of curvature on the magnitude of the grip forces and on the balance of forces between the two digits. We now repeat that analysis at a number of points during the initial phase of the task. Figure 6D shows grip forces for both digits at time points where the load force was 10, 50,
or 90% of the static load and shows the maximum grip force. There was no reliable effect of surface curvature on grip force at any of these time points ($P > 0.15$ in all cases). The asymmetry in grip forces applied by the two digits apparent in the static phase (thin lines in the figure) was not observed until the object had been lifted off the table and tilted slightly. In contrast, the asymmetric distribution of the load force between the two digits was present during the load phase, before lift-off (see Fig. 1C); throughout the load phase, the relative difference in load forces for the two digits was similar to that observed in the static phase. This indicates that the asymmetry between digits recorded during the static hold phase was a consequence of different rates of load force increase during the load phase, and as a result, the object tilted after lift-off (see Edin et al. 1992).

As with our analysis, in Fig. 4, of the force coordination during the static phase, we examined the correlation between slip ratio and employed grip-to-load force ratio for each digit for individual subjects. The employed ratio for the index finger was influenced by changes in slip ratio in only three of the eight subjects and only at the end of the load phase (LF90%); the correlation coefficients were 0.38, 0.38, and 0.45. For these three subjects, there was also a positive correlation for the thumb (coefficients 0.23, 0.28, and 0.40, respectively). These findings suggest that changes in slip force, induced by changes in curvature, had an even weaker influence on the force coordination during the dynamic phase of the trial than during the static phase for which six subjects showed a positive correlation.

**DISCUSSION**

The results of the present study demonstrate that when subjects lifted and held objects of various weights, the surface curvature of the object had little or no effect on the magnitudes of the fingertip forces used. Similarly, in the load phase before object lift-off, when grip forces and load forces increased isometrically, the duration and rate of force generation were not influenced by surface curvature. In contrast, there was a robust influence of surface curvature on the minimum grip forces required to prevent frictional slip. Consequently, the safety margin against frictional slips used by subjects was influenced by surface curvature; it was higher for the markedly concave and convex surfaces than for the flatter surfaces.

**Variation in slip ratio with changes in surface curvature**

The critical grip-to-load force ratio at which slip occurred, termed the slip ratio, decreased when the surface curvature...
became concave or markedly convex. When gripping objects with parallel flat grasp surfaces, the slip ratio corresponds to the inverse of the coefficient of friction between the skin and the object. With curved surfaces, however, the slip ratio reflects not only the friction but also additional factors related to the complex mechanical contact between the surfaces and the digits (e.g., Howard and Kumar 1996; Howe and Cutkosky 1996).

The visco-elastic fingertip will, to some extent, mold to the curved surface of the grasped object. Although the exact distribution of force vectors within the contact area is unknown, the load-related force components are likely to be distributed mainly in the lower part of the contact area for convex surfaces and in the upper part for concave surfaces. Thus in terms of fingertip forces, lifting an object with concave or convex surfaces is analogous to lifting an object with flat contact surfaces that taper downward. For obvious mechanical reasons, the slip ratio when lifting an object with such tapered flat surfaces is smaller than for objects with parallel grasp surfaces even though the friction between the skin and the surface material remains constant (Jenmalm and Johansson 1997). However, although there are some similarities between a change in the angle of tapered flat surfaces and a change in curvature, the nature of the contact with the finger is quite different; for both convex and concave surfaces, there are regions of contact where the tangents to the surface have positive, zero, and negative angles with respect to the vertical.

There was some variability across subjects with regard to the effect of surface curvature on the slip ratio (Fig. 2C). This idiosyncratic variability probably is due to differences in digit mechanics including anatomic and biomechanical factors such as nonlinear anisotropic elastic compliance, patterns of papillary ridges, sudomotor activity, and degree of greasiness and hydration of the skin (cf. Cadoret and Smith 1996; Häger-Ross et al. 1996; Johansson and Westling 1984b; Moore 1972; Smith and Scott 1996; Smith et al. 1997). A second possible source of variability between subjects is a difference in the way they contacted the surfaces. However, our measurements of the manner in which subjects gripped the object indicate small deviations in this respect (see METHODS). All subjects appeared to grasp the object at faces compared with flat grasp surfaces in fact may be functional constraints that were automatically controlled for during manipulation. When humans manipulate small irregularly shaped objects by gripping them with two digits, they typically strive to select grasp points that result in a grasp axis that is normal to local surface curvatures at both contact points (see Blake 1992; Goodale et al. 1994). With our test object, such an axis always passes through the centers of the curved surfaces. Interestingly, Weinstein et al. (1991) found that force coordination during precision grip was influenced less by instructions given to the subject than by intrinsic task variables related to the goal of maintaining a stable grasp.

Sparse adjustments of fingertip forces to changes in surface curvature

Surface curvature had no statistically significant effect on the grip forces used in the static hold phase when averaged across the eight subjects. However, within subjects there were small effects of curvature as shown by the relationship of employed grip-to-load force ratios and slip ratios (which are a more direct indicator of the force requirements for grasp stability than surface curvature as such). In six of our eight subjects, the grip-to-load force ratio reflected variations in the slip ratio associated with changes in surface curvature. However, even in these six subjects, the influence of the slip ratio on force coordination was small; the slope of the relationship between the employed ratio and the slip ratio was low (on average ~0.5), and there was considerable scatter in the data (low r values). In contrast, the corresponding slope is around unity for slip ratio changes resulting from changes in an object’s surface material (Johansson and Westling 1984a; Westling and Johansson 1984) or changes in the angle (taper) of flat grasp surfaces (Jenmalm and Johansson 1997). Moreover, the fingertip forces are robustly influenced by the slip ratio during the entire load phase when the surface material or the taper is changed. In the present study, corresponding influences of curvature during the load phase were observed in only three of our eight subjects, and they were weak.

Our data appear to be in conflict with the general principle of robust regulation of grip force that has been established in tasks where flat surfaces are grasped. This is an unexpected result because most objects that we handle have some curvature. Grip forces used by subjects for the markedly convex surfaces were similar to those used for the flat surface and, as a result, safety margins were higher for these curved surfaces. This apparent grip force excess seems nonpurposeful and seems to reflect a poor capacity to regulate grip force. However, there are two additional factors to consider. First, a small frictional slide, or a slight position bias, in the direction of the applied load force when grasping convex surfaces would lead to a contact geometry similar to that when grasping an object with flat surfaces tapered in the direction of the load forces. This would increase the grip force demands and threaten grasp stability if the grip forces were too small (Jenmalm and Johansson 1997). Thus the higher safety margins we recorded with convex grasp surfaces compared with flat grasp surfaces in fact may be functional if grasp stability is considered in this wider context. Second, in most everyday tasks where objects with curved surfaces are manipulated, in addition to linear load forces there would be torsional loads (cf. Kinoshita et al. 1997). When these tangential torques are taken into account, grip force is regulated robustly with changes in surface curvature (Jenmalm et al. 1997). The additional grip force required for highly curved convex objects may be part of a broader strategy to cope with such torsional loads (Jenmalm et al. 1997). It has been shown previously that the sensorimotor programs employed in manipulation reflect the diverse consequences of potential frictional slip (Häger-Ross et al. 1996). For instance, the onset latencies of grip responses triggered by load perturbations are some 10 ms shorter for perturbations in the direction away from the palm and in the direction of gravity than for perturbations in the opposite directions. The shorter grip response latencies for perturbations in certain directions appear to reflect a default scheme for the central nervous system to issue rapid responses to loads in these directions (cf. Favilla et al. 1990).
We also found higher, apparently inflated, safety margins when our subjects grasped the concave surfaces; these cannot be explained by the above arguments. Because of the effective outward taper of concave surfaces, maintaining grasp stability is less critical, in terms of force requirements, than with convex surfaces. If subjects used the same force coordination strategy with concave surfaces as with flat surfaces, accidental frictional slip always would be prevented but at the expense of more work from the muscles than if the grip forces were downregulated. Most humans seldom lift objects with spherically concave surfaces, and therefore they may not have developed control systems that respond to the decreased grip force demands in this situation. In addition, from an efficiency point of view, it may be advantageous to ignore the surface curvature and consider only the friction between the object and the skin when determining the required grip-to-load force ratio; the demands on sensorimotor processing probably would be less than if a full regulation were performed and a stable grasp still would be maintained.

Possible role of tactile afferent information about surface curvature

Contact between the digits and the object excites cutaneous mechanoreceptors that provide a wealth of information about the object. When objects are presented passively to the fingertips, humans possess a remarkable ability to discriminate small differences in surface curvature (Goodwin et al. 1991) and small difference in the position of contact (Wheat et al. 1995). Details of the local shape of the object and the point of contact may be encoded mainly by the populations of slowly adapting type I (SA I) cutaneous afferents (Goodwin et al. 1995, 1997; LaMotte and Srinivasan 1987a,b). Apparently this information on surface curvature is not used directly to adjust grip forces when lifting objects because changes in surface curvature had only small effects on the employed fingertip forces. However, cutaneous afferent information on local shape and contact position is necessary to control the motor output during position- ing of the digits on curved objects. Selection of appropriate grasp points is crucial for grasp stability. Normally, visual information also will contribute to this selection (e.g., Goodale et al. 1994), but when we use our digits to manipulate small objects in the dark or when the objects are out of sight, haptic exploration must be used. In such situations, signals in the population of SA I afferents would play a prominent role in controlling the motor output.

Tactile afferent information is of prime importance in the adaptation of fingertip forces to changes in friction between the grasped surfaces and the skin. Most of this adaptation occurs soon after the object is touched (Edin et al. 1992; Johansson and Westling 1984a), and the relevant afferent information most likely is conveyed by FA I afferents, which show rapidly adapting response characteristics (Johansson and Westling 1987). Changes in surface curvature seem to have little effect on the use of afferent information related to friction; regardless of curvature, the used grip-to-load force ratios were appropriate for the frictional condition as reflected in the slip ratios obtained with the flat grasp surfaces.

Thus peripheral sensory information related to surface curvature and that related to surface friction appear to be used differently in the control of manipulation.

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