A Physiological Method for Relaying Frictional Information to a Human Teleoperator

Benoni B. Edin, Robert Howe, Göran Westling, and Mark Cutkosky

Abstract—**The ability to sense and respond to frictional variations is important for dexterous manipulation. It has been demonstrated that humans apply forces to an object on the basis of its anticipated frictional properties. After contact, tactile receptors provide information on the actual frictional properties and ensure that the applied finger tip forces allow for a safety margin against slips during the ensuing manipulation. With inappropriate forces, incipient and overt slips occur which produce receptor discharges and elicit automatic adjustments of the finger tip forces to increase the safety margins against future slips. It is demonstrated that it is possible to elicit rapid, nonhabituating and sustained grasp responses by means of a tactile display. Subjects grasped and lifted an instrumented test object using the thumb and index finger. While the object was held in air, rapid but small sliding movements were invoked between the object and either contact plate and caused a load force redistribution. This reliably triggered a grasp force increase similar to the ones elicited by natural slips occurring during normal manipulation. An important application of this finding is in relaying frictional information from a slave hand to a human operator. Furthermore, it may make it possible to reduce disparity between master and slave hands in force reflective telemanipulation systems.**

I. Introduction

The ability to sense and respond to variations in friction is important for dextrous manipulation because many manipulative tasks depend on the ability to prevent objects from slipping from a grasp. The need to prevent slippage must, however, be balanced against the need to minimize grasp forces to conserve effort and to avoid damage to fragile objects. Humans are able to choose a grasp force that is near the minimum effective value over a wide range of object weights and surface friction by using tactile sensory information [1], [2]. Neurophysiological experiments provide evidence that even local slips that do not cause a sliding movement at the contact result in appropriate adjustments of the grasp (or normal) and load (or tangential) forces. These automatic adjustments always lead to an increase in the normal:tangential force ratio, which reduces the chance of further slips.

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A similar approach has been used to control grasp forces in robot and prosthetic hands. Electromechanical slip sensors have been developed that can detect the minute vibrations that indicate the earliest stages of slip (e.g., [3], [4]). These sensors have been mounted in the contact surfaces of the fingers of mechanical hands, and their signals have been used to trigger an increase in grasp force when incipient slip is detected [5]–[7].

These results have important implications for teleoperated dextrous manipulation, particularly with force feedback. In such manipulation a human operator interacts with a master manipulator to control a slave robot hand that may be located in a remote hazardous environment. Although there is considerable current interest in this area, little experimental work has appeared in the literature (see [8], [9] for a recent review). Prior work with teleoperation of robot arms has demonstrated that force feedback provides significant improvement in performance in contact tasks [10]. Both mechanical analysis and physiological evidence suggest that force information will be even more important in dextrous telemanipulation [11].

The normal grasp control is crucially dependent on information about the frictional conditions at the digit–object interfaces. Force feedback in dextrous telemanipulation thus raises the issue of relaying this frictional information from the slave manipulator to the human operator. Electromechanical slip sensors mounted in the slave manipulator finger tips can measure the friction, and a number of methods may then be used to relay this information to the operator. The simplest approach, sensory substitution techniques using visual or audio displays (e.g., [12]), seems undesirable for several reasons: the display may require conscious attention, is likely to decrease performance by increasing latencies, and may increase operator fatigue. A preferred approach is to present mechanical stimuli to the human operator that trigger the same physiological responses as when an object is directly manipulated by the human hand.

As mentioned above, human grasp control is based on signals from tactile sensory organs. During grasp-and-lift manipulation tasks, small slips elicit short bursts of responses in a variety of tactile receptors [13]. Burst activity has also been artificially elicited using pulsed electrical stimulation of the skin in contact with an object [14]. However, humans adapt to such stimulations and cease to respond after just 2 to 3 trials. Thus, electrical skin stimulation is not useful for relaying information about slips. The reasons for this failure might be found by considering the physical phenomena that occur during slip, and the consequent sensory responses. When an object is held by two digits and a slip occurs at one digit, this typically will not cause the object to drop but will result in a rapid redistribution of the load forces. If the object has a low center of gravity, the tangential force is decreased at the slipping digit while increased at the other digit. Such passive redistributions have been reported in humans and are always followed by force adjustments that commence in 60–90 ms [14]. In addition to the tangential force redistributions, slips induce vibrations at the contact areas. The reason why electrical stimulation fails to elicit the desired grasp force control response may be that the sensory signals evoked by electrical stimulation, while superficially resembling the ones evoked by a slip, lack the normal temporal and spatial pattern.

The paper reports on experiments which demonstrate that the combination of a sudden tangential force redistribution and vibrations are adequate to initiate nonhabituating and seemingly normal grasp force responses. Such stimuli could in theory be employed to relay frictional information between a teleoperated hand and a human operator. We review the experimental methods, present the results, and discuss the implications of the findings to teleoperated manipulation.

II. Method

A. Subjects and Task

Four subjects, naive to the objectives of the study, participated after giving their informed consent. Their task was to lift a test object using the right index finger and the thumb. The object was lifted a few cm up in the air, held for about 5 seconds, and then replaced. The exact timing of the different phases of the task was not crucial but the whole sequence was usually completed in less than 10 seconds.

B. Test Object

The instrumented test object had a center of gravity 110 mm below the contact areas and a mass of 350 g. The contact areas were covered with fine sandpaper and measured 35 × 35 mm. On the back of each contact area, a rectangular plate was mounted that fitted a depression on each side of the object. This plate's height was 0.5, 1.0, or 2.0 mm less than height of the depression. The friction between the plate and object itself was low. The contact plates were kept in vertical position by a solenoid (see Fig. 1). When the current through the solenoid was interrupted, the plate was free to move upwards until it met a mechanical stop, i.e., the upper edge of the depression on the object. Plate movements of 0.5, 1.0, and 2.0 mm were possible depending on the contact plate used. The contact areas were thus kept in position by the solenoid but allowed to move upwards as a result of the tangential force applied by the subject's digit as soon as the current through the solenoid was shut off. The solenoids for the thumb and index finger were controlled separately.

C. Experimental Runs

Two basic sets of series were designed. One series consisted of 8 consecutive trials with the same amplitude of contact plate movements (0.5, 1.0, or 2.0 mm), totaling 24 trials. The other series consisted of 25 trials with 1.0 mm release amplitude but an unpredictable sequence of plate release conditions occurring in pairs of equal likelihood (index followed by thumb, index followed by index, etc.). Plate release was manually controlled by the experimenter. There were no trials without a plate displacement. Masking noise through headphones was used to circumvent auditory cues. Data from 8 sequences, including 181 lifts, were analyzed. Lifts in which plate release occurred in other phases of the lift than when the object was held in the air were excluded to simplify analysis of grip force responses.

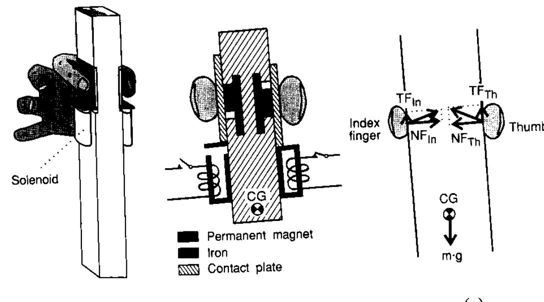

Fig. 1. Instrumented test object. (a) Object held in air. (b) The solenoids were attached to the frame of the object and kept the contact plates in the lower position as long as the current was on. When the current through one of the solenoids was switched off, the corresponding contact plate moved upwards resulting in a tangential force redistributions as indicated in (c).

D. Data Collection and Measurements

Normal tangential forces were recorded using separate strain gauges for the index finger and the thumb (dc-120 Hz). To detect vertical mechanical transients the signal from an accelerometer on the object was recorded (dc-600 Hz); this signal was root-mean-square processed with rise and decay times of 3 and 6 ms, respectively. The vertical position was recorded with an ultrasonic position transducer, where the transmitter was in the object and the receiver in the ceiling (dc-120 Hz). The contact between the table and the object was measured electrically. The filtered transducer signals were digitized to 12 bits at 400 Hz. Time derivatives of all forces were calculated as a function of time using 4–point numerical differentiation. Static values of normal and tangential forces at release of the contact plate, impact of the plate on the mechanical stop, first sign of increase in normal force, first peak of normal force, and force values of 0.8 s after plate release were measured (cf. Fig. 2).

III. Results

Three phases can easily be identified in single trials as previously shown and defined [1]: the load, hold, and release phase (see Fig. 2). During the load phase, the normal and tangential forces are increased in parallel until the object is lifted from the table. After holding the object supported only by the finger for a few seconds it is returned to the table. During the release phase, which commenced shortly after contact with the table, the normal and tangential forces are decreased in parallel.

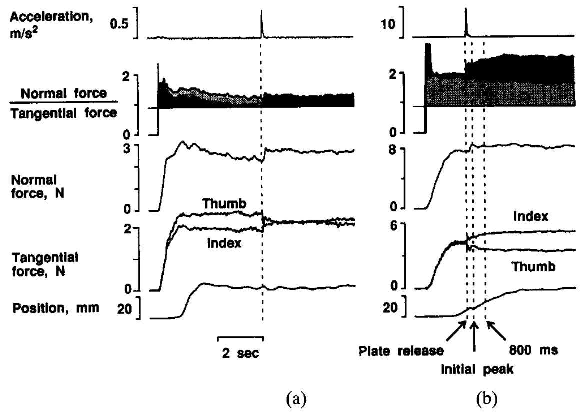

Fig. 2. (a) Spontaneous slip. During the slip there is a rapid decline in tangential force at the slipping digit and a concommitant increase at the other digit. This redistribution restores a significant safety margin at the slipping digit but decreases the safety margin at the nonslipping digit. As a response to the slip, there is an increase in normal force in about 80 ms and this further increases the safety margin that slipped and restores the safety margin at the other digit. Note that the safety margins tend to decline during the hold phase due to a gradual reduction in employed normal force. (b) Plate release. The plate at the thumb was released during the hold phase (vertical line) causing a tangential force redistribution followed by a grip force responses similar to the one in (a). Normal and tangential forces were measured at plate release, at the initial peak of the normal force and at 800 ms after the release. Slip ratios are indicated by horizontal lines, safety margins by darker gray for the thumb and lighter gray for the index finger.

Overt slips are rare events, occurring in less than 5% of the trials, even when the frictional conditions are varied between lifts [15]. A record from a trial including such an event, obtained in an experimental series not involving external disturbances, is shown in Fig. 2(a) [16]. A test object similar to the one in the present study was used. When the slip occurred, an immediate redistribution of the tangential forces was observed. This redistribution resulted in a decrease of the tangential force at the slipping digit and an increase of the force at the other digit. As a consequence of this, the safety margin against future slips was increased at the slipping digit and decreased at the nonslipping digit. Thus, these events stabilize the grasp (unless the safety margin against slip at the nonslipping digit was so small that a further reduction would cause a secondary slip at that digit as well). After a latency of 90 ms following the slip, there was an early increase in the normal forces followed by a sustained increased normal:tangential force ratio. The sustained increase in the ratio is considered the functional response, since it will reduce the likelihood of future slips [2].

In the lifting trials for this experiment, plate releases also produced both an early increase in the normal force and a sustained increase in the normal:tangential force ratio (see Fig. 2(b)). This response was observed in all subjects, but with some individual variations, as discussed below.

A. Initial Responses

The plate at the index finger or the thumb was released during each hold phase. This release always resulted in a rapid redistribution of tangential forces (see Figs. 2(b) and 3). The time required for completing the redistribution of tangential forces was dependent on the release amplitude. The theoretical minimum movement times assuming free fall are 10, 14, and 20 ms for the 0.5, 1.0, and 2.0 mm release amplitudes; the measured time to impact was only slightly larger than these values and never larger than 25 ms (due to friction between the object and the sliding contact plate the object was never in free fall).

Following plate release, normal force began to increase after a mean latency ranging from 83 to 113 ms (83 ± 14, 113 ± 12, 93 ± 23, 83 ± 21 ms, mean ± SD for individual subjects), and reached a peak after another 125 ± 34 ms (there were no significant differences between subjects). Thus the total time from the plate release to the first maximum of the normal force was about 200 ms. Although the latency to the increase in normal forces was smaller with larger release amplitudes (Spearman, $p < 0.01$ in all subjects), the magnitude of this effect was small. Data on the latency from onset of slip to force increase in natural slips has been reported to be 74 ± 9 ms [14]. Thus, if the time from the plate release to impact is subtracted from the latencies obtained in the current study, they are similar to previously reported latency data.

The amplitude of the first maximum of normal force increase following plate release averaged 0.56 ± 0.32 N. This corresponds to about 10% of the averaged normal force applied at the moment of plate release. The normal force increase was not scaled to the normal force at the time of perturbation ($r = 0.27$, $p > 0.1$). Normal force increases were observed for all trials with the 1.0 and 2.0 mm release amplitudes, but failed to occur in a small number of trails with the 0.5 mm release amplitudes.

Although the passive and active load redistributions resulted in test object tilting of not more than few degrees, the effect on the normal:tangential force ratios was marked (see Figs. 3(b), 4, and 5). The ratio increased for the digit at which the slip occurred, while the ratio at the other digit was virtually unaffected (cf. [16]).

Plate releases at both digits were effective in eliciting responses and no significant differences in latencies or grip response magnitudes were observed between the index finger and the thumb. In fact, when the two plates were released in succession, both resulted in adjustments of the normal:tangential force ratio (see Fig. 4).

B. Sustained Responses

To get an estimation of the sustained increase in normal forces, the differences between the force immediately before the plate release and 0.8 s thereafter were calculated. The sustained increase was lower than the initial peak in normal force (0.23 ± 0.41 N, mean ± SD). Two subjects, in particular, showed a strong decline in normal forces during the hold phase. The plate release response in these subjects seemed to be superimposed on this steady decline, and the normal force 0.8 s after the release was higher than it would have been without the plate release see (see Figs. 2(a), 3(b), and 4). In the other two subjects the mean decrement in the normal force from the time of initial peak to 0.8 s was small (from 0.60 N to 0.51, and from 0.67 to 0.45, respectively).

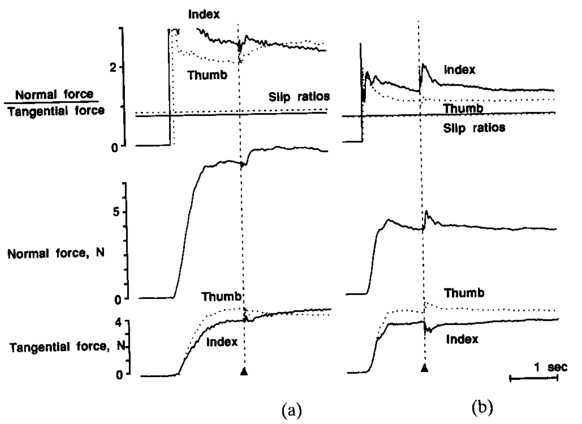

Fig. 3. Two sample releases. (a) shows a plate release (vertical line) at the thumb, (b) at the index finger. The tangential force at the digit in contact with the released plate decreased rapidly while it increased at the other digit. In less than 100 ms a grip force increase was observed that increased the safety margin at both digits. Notably, these effects were quite digit specific, i.e., the safety margin definitely increased at the digit with a plate release but only restored the safety margin at the other digit.

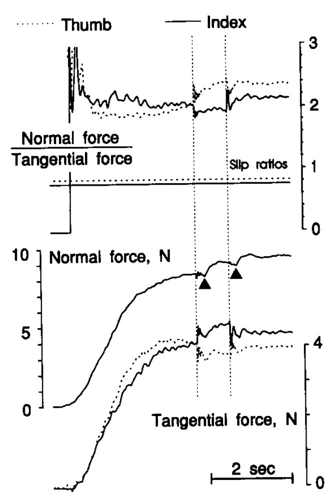

Fig. 4. Consecutive plate releases. The plate at the thumb was released followed about 1 second later by a plate release at the index finger (vertical lines). Both elicited significant grip force increases (arrow heads), as evident in the normal force trace, and also appropriate increases of the normal:tangential force ratios at both digits.

Although larger release amplitudes resulted in significantly larger sustained ratio increases than small release amplitudes (Spearman, $p < 0.05$ in 3 out of 4 subjects), the absolute effect of this was not large and could mainly be seen when comparing the responses of 0.5 mm and 1.0 mm releases with the 2.0 mm releases.

C. Habituation and Expectation

When the responses early and late in a series were compared no significant differences were observed in any subject (see Fig. 5). In fact, robust responses were elicited even when the subject in separate test series had been informed that plate releases rather than true slips would occur. Although

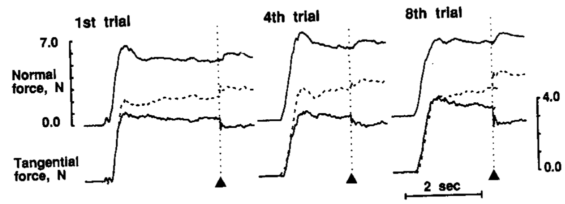

Fig. 5. Lack of habituation. The first, fourth, and eighth trial in a series of eight trials with 1 mm plate releases at the index finger. While the normal force increase varied slightly in amplitude from trial to trial, there was no tendency for the responses to habituate.

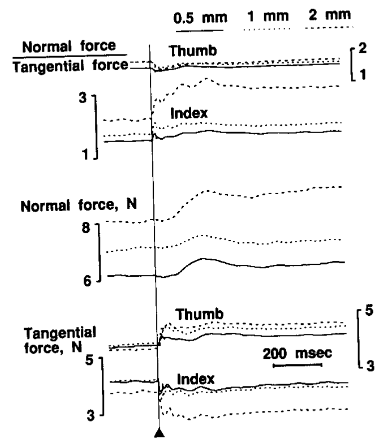

Fig. 6. Effect of release amplitude. Averaged responses to a series of eight trials in one subject with index finger plate release amplitudes of 0.5, 1.0, or 2.0 mm. The vertical line indicates the time of plate release. With all amplitudes the increases in the normal forces were elicited in 80–120 ms with resulting sustained increases in the normal:tangential forces ratio at the index finger. Note that the averaged preperturbation normal:tangential force ratio was significantly larger in series with larger plates releases.

no significant effects of release amplitude were observed in the response based on pooled data, it had a strong biasing effect on the normal:tangential force ratio. With all subjects, higher preperturbation normal forces were employed in series with the 2.0 mm release amplitude than with 0.5 mm release amplitude (see Fig. 6).

D. Subject's Report

All subjects noted that "something was wrong with the test object," and a few suggested that one or the other of the plates were not properly attached to the object. None remarked that the object behaved as if it was slippery.

IV. Conclusion

This paper demonstrates that it is possible in humans to elicit robust physiological responses that are very similar to the responses observed with naturally occurring slips. Since the responses elicited by redistributions during grasping are non-habituating, they may be useful in reducing disparity between master and slave hands in force reflective telemanipulation systems.

Humans have a remarkable ability to manipulate objects with different mechanical properties and surface characteristics so that overt slips are rare. When they occur, however, they typically result in a slip-and-stick event at just one digit causing a rapid tangential force redistribution between the digits involved in the grasp. The normal:tangential force ratios are subsequently actively adjusted to increase the safety margin against future slips. These adaptions are important because the time required from detecting a slip to a significant increase in normal force is more than 100 ms, i.e., much longer than would be required to catch a fully sliding object. Thus, successful manipulation in humans is based on anticipatory control.

Appropriate feedback channels unfortunately do not exist in telemanipulation for eliciting the anticipatory control mechanisms that characterize human manipulation. One effect of this is the potential for grasp force disparity between a master and a slave manipulator. For instance, slip sensors in the slave hand's fingers might detect small slips, and in responses to this the slave's local controller can increase the grasp force before the object is lost. However, the grasp force at the slave manipulator will then be larger than the grasp force at the master. This undesirable disparity can be eliminated by using a tactile display to trigger grasp force increases in the human when small slips are detected at the slave hand. Using normal human grasp responses rather than an indirect cue means that the operator's conscious attention is not required. This is likely to both improve performance and reduce operator fatigue.

A. Physiological Implications

The findings are remarkable in that the induced force redistribution most likely did not result in a neural activity identical to the one elicited by natural slips. Indeed, the stimuli used in this study were recognized as artificial by all subjects. Nevertheless, seemingly normal motor responses resulted. There are three components of the mechanical stimulus which probably play some role for the behavior: the rapid load force redistribution, small-amplitude vibrations when the contact plate is released by the solenoid and slides upwards, and a large-amplitude vibration induced by the impact of the plate. It is not possible to infer from the results exactly which components are sufficient to trigger the grasp reflex, but timing information may provide some insight. The delayed increase in normal force seems to indicate that the timing of the response was determined by the impact rather than by the tangential force redistribution per se. This suggests that either impact-induced vibrations or local slips are important. The timing of the inputs was probably different from natural slips in which vibrations and load redistribution commence at about the same time, whereas load redistributions precede significant vibrations with the tactile display used in this study. Since normal physiological responses were elicited, timing errors between different afferent channels in the somesthetic system of about 10 ms seem to go unrecognized by the portions of the CNS engaged in grasp control.

There is physiological evidence that different receptors are responsible for detecting tangential and normal forces (SAII receptors) and for detecting mechanical transients such as those caused by slips (FA and perhaps SAI receptors) (for a review see [2]). It seems reasonable to hypothesize that a particular pattern of changes in the neural inputs constitute a slip to the CNS (cf. the effects of electrical stimulation described above [14]). The hypothesized pattern recognition mechanism may also explain the lack of responses in a few trials with small amplitude releases. If the impact of the plate with the mechanical stop did not cause local slips, a crucial component of the normal neural activation pattern may have been missing. This may have been correctly interpreted by the subject, i.e., that no slip had occurred.

B. Unresolved Issues

It is encouraging that normal physiological responses can be elicited in a manipulative task by very simple means. However, human motor control systems are complicated, and the present study does not necessarily imply that the stimuli used here represent a means of relaying frictional information in more complex tasks. Further study of automatic human motor responses to patterns of spatial and temporal stimulus is needed. We have developed a teleoperated hand system specifically for the study of tactile sensing and display in dextrous telemanipulation (see [17]). We hope that this system will enable us to test the ability of this type of display to effectively relay frictional information in a variety of tasks.

One important issue the present study has not addressed is the effect of latencies and delays in the tactile display and the operator's response. Early work on force-reflecting teleoperation showed that delays of only a fraction of a second lead to instabilities [18]. Detecting slips by means of electromechanical sensors and subsequently relaying this information to the human operator must add to the latencies from slip detection to motor response. The magnitudes of these additional delays as well as their effects, if any, on the operator and on the manipulator system are unknown and must be explored.

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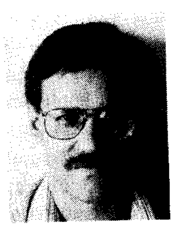

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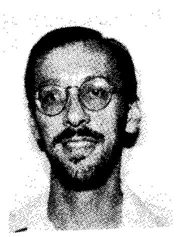

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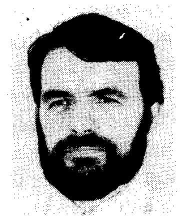

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