Psychophysical Characterization and Testbed Validation of a Wearable Vibrotactile Glove for Telemanipulation

Abstract

This paper describes and evaluates a high-fidelity, low-cost haptic interface for teleoperation. The interface is a wearable vibrotactile glove containing miniature voice coils that provides continuous, proportional force information to the user's fingertips. In psychophysical experiments, correlated variations in the frequency and amplitude of the stimulators extended the user's perceptual response range compared to varying amplitude or frequency alone. In an adaptive force-limited pick-and-place manipulation task, the interface allowed users to control the grip forces more effectively than no feedback or binary feedback, which produced equivalent performance. A sorting experiment established that proportional tactile feedback enhances the user's ability to discriminate the relative properties of objects, such as weight. We conclude that correlated amplitude and frequency signals, simulating force in a remote environment, substantially improve teleoperation.

1 Motivation

We have all experienced that when wearing gloves on our hands it typically is more difficult to perform a manipulative task than if we had used our bare-hands. This effect has been measured with divers and astronauts where thick gloves are worn and difficult manipulation tasks are performed (Banks & Goehring, 1979; Chodack & Spampinato, 1991). Taking a step further by anesthetizing the fingertips, Johansson and Westling (1984) showed that we are unable to coordinate grip forces to lift objects successfully without tactile sensations. We consider teleoperating a robotic hand without tactile feedback to be like having a person wear gloves while performing everyday manipulative tasks; thus, we believe that by providing tactile feedback to a human operator, he/she will be able to perform dexterous telemanipulation tasks more effectively. The work we present here is our attempt to demonstrate quantitatively that tactile feedback is useful for manipulative tasks in remote environments.

Our initial research began by attempting to meet this goal using binary shape memory alloy (SMA) "tactors" to convey grip force information to a user performing a pick-and-place telemanipulation task. The results failed to prove any significant gain in operator performance over visual feedback alone (Murray, Klatzky, Shimoga, & Khosla, 1997). Our hypotheses for this failure were two-fold. One, we thought that the very essence of binary feedback did not help the operator; that is, for binary feedback the stimulation was either "on" or "off" and not proportional, so when the stimulators turned "on" and starting pulsing, no additional information was conveyed to the operator about the progression of grasp forces. Second, we did not use cooling techniques (Hunter, Lafontaine, Hollerbach, & Hunter, 1991; Wellman, Peine, & Howe, 1997) or sophisticated control schemes (Kontarinis & Howe, 1993) to minimize the actuation delays of the tactor's shape memory alloy wire; we believe this activation latency also contributed to poor operator performance when compared to immediate visual feedback.

These results spurred the development of a vibrotactile glove using miniature voice coils to address our concerns. The glove provides continuous vibrotactile feedback to the user and does not exhibit actuation latencies. To optimize the human operator's interaction with the remote environment, we characterized the user's response to the glove's vibrotactile stimulation. This characterization was accomplished through a series of psychophysical experiments to evaluate a human operator's sensitivity to vibration on his/her fingertips. We conducted three such experiments. The first two experiments examined how to vary the glove's vibrations optimally in order to provide discriminable stimuli to the wearer by measuring the user's response to variations in a single voice coil's signal amplitude and frequency. Our third psychophysical experiment extended this work to investigate interaction with multi-finger vibrotactile stimulation.

To measure the quantitative utility of the vibrotactile glove in a telemanipulation environment, we conducted telemanipulation experiments from which objective measures (e.g. task completion time and mean grip force) were used to evaluate the feedback. This approach was much like what had been done in the past for force-reflective (i.e., wrist and arm level force feedback) master-slave systems (e.g., Hannaford, Wood, McAffee, & Zak, 1991). In the work we present here, the telemanipulation tasks were performed with visual feedback only (also referred to as the no-tactile-feedback condition) and with visual and tactile feedback. The no-tactile-feedback condition served as a baseline for the performance with the tactile feedback. We conducted two such telemanipulation tasks to evaluate the ability of tactile feedback to convey important touch and finger force information to a human operator. Both experiments involved perception-intensive variants of a basic pick-and-place manipulation task.

A secondary objective of the telemanipulation experiments was to refute or support our hypotheses from our preliminary investigation with binary shape-memory alloy (SMA) tactile feedback. The force-limited pick-and-place experiment we present below (Experiment 4) allowed us to examine these issues directly. Specifically, we performed this experiment with the vibrotactile glove operating in a binary mode and, as a result, eliminated problems with actuation delays we found in our preliminary work with the SMA tactors. From this experiment, we were able to draw strong conclusions about the ineffectiveness of binary tactile feedback.

2 The Vibrotactile Glove

At the Advanced Mechatronics Laboratory at Carnegie Mellon University, we have developed a vibrotactile glove system that is wearable, affordable, and allows continuous transfer of information with low actuation latencies. The vibrotactile glove uses miniature voice coils that are commonly used in small audio electronic devices (see Figure 1). The voice coils are small (20mm diameter, 4 mm thick) and lightweight enough (1.7g) to place on a user's fingertips without encumbering natural hand movements; these features have allowed us to integrate the stimulators with the Cyberglove™ by using velcro patches and straps sewn inside the glove's fingertips. The stimulators have a high bandwidth (DC to 5kHz frequency range; LZR Electronics, 1998) and are reliable and inexpensive. The glove's electronics allow the Chimera real-time operating system (Stewart, Schmitz, & Khosla, 1992) to independently and simultaneously control the amplitude, frequency, and wave type (sine or square) of each stimulator. At this time, we can operate up to six stimulators, but more stimulators can be added to the system if desired, since a modular electronic design approach is used.

Insert Figure 1 about here

The frequency response and the displacement of the voice-coil stimulators were measured while worn on users' fingertips using a laser-doppler vibrometer. The voice coils exhibit a second-order behavior and have a resonant frequency of 900 Hz in an unloaded state (i.e., free-standing, no fingertip) and approximately 450 Hz in a loaded state (i.e., with the stimulator on a fingertip). However, for the glove's normal operating condition in a frequency range of 25 Hz to 300 Hz, which is determined via the psychophysical experiments described below, the frequency response is fairly flat. In this operating range, the average unloaded displacement of the voice coil is –27 dB (ref. 1 mm/V) or 43 microns/V, and the average loaded displacement is –38 dB (ref. 1 mm/V) or 13 microns/V. The stimulators' displacement while worn is well within the minimum detection threshold range of 4 microns at 50 Hz to 0.2 microns at 250 Hz (Sherrick & Cholewiak, 1986; Verrillo, Fraioli, & Smith, 1969).

3 Psychophysical Experiments

This section describes three psychophysical experiments we have conducted to examine a user's sensitivity to single-finger and multi-finger vibration provided by the vibrotactile glove. In the first experiment, we demonstrate that the miniature voice coils we have selected for our vibrotactile glove design are capable of producing discriminable vibrotactile information to a user. In the second experiment, we extend this work and show that co-varying the signal amplitude and frequency of the voice coil increases the user's perceived magnitude range compared to the more conventional approach of varying only the amplitude of a fixed-frequency signal. In the third psychophysical experiment, we show that stimulating multiple fingers simultaneously increases the perceived intensity, but by a rule of diminishing returns.

3.1 Experiment 1: Effects of Frequency and Amplitude on Perceived Vibratory Magnitude

This experiment was intended to determine how the frequency and amplitude of a vibration affected its perceived magnitude, that is, to characterize the psychophysical function for these two control parameters of the signal. Determining the psychophysical function is essential to our goal of providing maximally discriminable signals to the user of a teleoperation system. In Experiment 1, we measured the perceived magnitude given variations in the signal amplitude or frequency alone. Others have considered amplitude effects in vibrotactile displays (Massimino & Sheridan, 1992; Patrick, Sheridan, Massimino, & Marcus, 1990; Tang, Beebe, & Kramer, 1997), but not with the present device. In the present study, frequency effects were also investigated. When frequency was manipulated, a fixed, suprathreshold amplitude was used; and when amplitude was manipulated, the frequency of the signal was fixed at 250 Hz, which was intended to maximally stimulate the Pacinian corpuscle receptors (Cholewiak & Collins, 1991).

3.1.1 Method

There were fifteen subjects (14 male, 1 female) from the university community at Carnegie Mellon (students and staff).

Each stimulus comprised three 600 ms pulses of a sinusoidal signal. There were 10 such stimuli in each of two conditions: amplitude-modulation (AM, having fixed frequency) and frequency-modulation (FM, having fixed amplitude). The AM stimuli had a frequency of 250 Hz (as noted above, based on the maximum Pacinian corpuscle response) and covered ten equally spaced signal amplitude values from a range of 0.25V to 2.5V. We chose those amplitudes because the lowest was reliably above detection threshold, and the highest was close to the maximum the voice coil could handle safely without overheating. The relation between the input voltages (signal amplitude) and the loaded displacements at the fingerpad is shown with the results in Figure 2. The FM condition used the maximum amplitude of the AM condition (2.5V) and ten frequency values from 50 Hz to 500 Hz, spaced at 50 Hz intervals. These frequencies were chosen to span the range around the peak Pacinian corpuscle response. The relation between the frequencies and the loaded displacements is shown with the results in Figure 3. Note that for both modulation conditions it is a special baseband modulation scheme in which the modulating terms (amplitude and frequency) are both non-negative and the carrier frequency is 0 Hz.

Insert Figures 2 and 3 about here

The subject's task was magnitude estimation with a free response (Zwislocki & Goodman, 1980). That is, the subject verbally gave a numerical response that represented the intensity or strength of the vibratory stimulus. No scale was specified, although zero was excluded. The stimulus was presented to the index fingertip of the dominant hand by having the subject place the back of his/her hand on a supporting surface, and attaching the voice coil's diaphragm on the fingertip using velcro straps. To ensure the subject was unable to hear auditory cues from the miniature voice coils stimulators, he/she wore headphones playing white noise.

Each subject participated in both the AM and FM conditions of the task. The order of conditions was counterbalanced across subjects. Each condition consisted of 30 trials, corresponding to three presentations of each of the 10 stimuli, in a fully random order.

On each trial, the subject was presented with the signal, which he/she could ask to have repeated if desired. The subject then gave the magnitude response. To acquaint the subject with magnitude estimation, the experiment began by having the subject give estimates for the lengths of lines presented visually on paper. This was followed by presenting the subject with several of the stimuli in the first condition, including the most and least intense, so that responses could be scaled accordingly. No feedback was given during this phase. This pre-exposure was performed prior to the second condition, which used different stimuli, as well.

3.1.2 Results and Discussion

To analyze the data, it is necessary to adjust subjects' responses for differences in the scales adopted (Zwislocki & Goodman, 1980). Accordingly, each subject's response was normalized by dividing by the subjects' mean in the given condition, then multiplying by the grand mean across the condition for all subjects. To create a more linear scale, the observations were then transformed by logs, and finally, the three observations for each stimulus within a given subject were averaged.

Figures 2 and 3 show the average responses by condition, as a function of the stimulus value, on a log-log scale. The AM condition led to a monotonic increase in log magnitude with increases in log amplitude, indicating that the subjects responded differentially across the amplitude scale. A linear fit to the log amplitude and log magnitude response reveals a slope of nearly one (slope = 0.9, y-intercept = 0.43) with an r^2-value of 0.99. This agrees with the trend Verrillo et al. (1969), and Verrillo & Capraro (1975) found when a rigid annular surface was used around a vibrotactile stimulator (slope = 1 at 250 Hz), which resulted in a slope (i.e., power law exponent) that was frequency-independent. Without the rigid surround, researchers found the exponent to be 0.58 at 250 Hz and to increase as the frequency decreased, reaching an exponent of 1 at 50/60 Hz (Franzen, 1969; Stevens, 1959, 1968; see summary in Kenshalo, 1978). This correlation with previous work suggests that the rim of the miniature speaker or the speaker's diaphragm itself is acting as a rigid surround.

In contrast, the FM condition showed a nonmonotonic trend, in the form of an inverted-U function with a peak at 300-Hz. This is consistent with the peak response of the Pacinian corpuscles around 250-350 Hz (Cholewiak & Collins, 1991). Again, this shows differential sensitivity across the input scale, albeit nonmonotonic. The log magnitude response can be approximated with a quadratic function ($r^2 = 0.71$); whereas a linear fit to the data (slope = 0.42, y-intercept = -0.39) is unable to effectively describe the response data ($r^2 = 0.45$).

The two conditions contained a common stimulus: 2.5V, 250 Hz, allowing us to compare the subjects' mean response at this point. The difference did not reach significance ($t(10) = 2.14$, $p = .058$), indicating that the response scales used by the subjects did not vary appreciably with the context of AM vs. FM modulation.

On the whole, the data show that variations in signal amplitude and frequency produced reliable differences in perceived vibratory magnitude. Moreover, they indicate that the response to frequency variations is nonmonotonic, as predicted by the tuning function of the Pacinian corpuscles. We take these results to indicate promise for providing feedback to a teleoperator in the form of vibrotactile stimulation. That is, it appears that users will be able to discriminate between the different values of vibration that represent different remote forces.

There remains the problem, however, of the nonmonotonic function relating perceived magnitude to frequency. To deal with this problem, Experiment 2 adopted a frequency range across which the perceived magnitudes increased monotonically with increasing frequency.

3.2 Experiment 2: Enhancing Perceived Vibratory Magnitudes

The purpose of this experiment was to determine if combining variations in amplitude and frequency would enhance people's differential sensitivity to a range of vibrotactile stimulation. If so, coupled AM/FM-modulated signals could be used to convey feedback in a teleoperation system so as to maximize the perception of differential forces in a remote environment. This combined AM/FM approach is in contrast to vibrotactile displays that modulate only the amplitude of a fixed-frequency sinusoidal signal to convey information to the user (Massimino & Sheridan, 1992; Partrick et al., 1990; Tang et al., 1997). Work of Verrillo and associates (1969), which determined equal-magnitude contours for vibrotactile signals varying in frequency and amplitude, suggests that the present approach will be effective. They showed that as stimulus frequency increased, the displacement amplitude required to produce a given subjective magnitude of vibration generally decreased over the range of approximately 15-300 Hz. Moreover, subjective magnitude increased directly with amplitude of displacement. Thus, their work suggests that a person's differential sensitivity to vibrotactile stimuli can be enhanced by modulating both the amplitude and the frequency of a sinusoidal signal simultaneously.

3.2.1 Method

Twelve subjects (6 male, 6 female) from the university community participated. The task was again magnitude estimation. Three conditions were used, in a within-subject design. The order of conditions was counterbalanced across subjects.

The AM condition used a 300-Hz fixed frequency – the level producing the maximum magnitude in Experiment 1. There were 6 stimuli varying from .76V to 2.5V in equal steps. The loaded displacements for these values are shown with the results in Figure 4. The FM condition used the maximum amplitude of the AM condition (2.5V) and six frequency values, from 50 to 300 Hz at 50-Hz intervals. The loaded displacements for these values are shown with the results in Figure 5. Note that within this range of values, the log magnitude estimates of Experiment 1 increased monotonically with log frequency. Thus one would predict an increase in log magnitude across increases in the manipulated variable within both the AM and FM conditions. The third condition was a combined amplitude-frequency modulation (AM-FM). The 6 stimuli for this condition were created by coupling the AM and FM values from the other conditions, in order, so that the lowest AM value and lowest FM value co-occurred in the first stimulus, the next-lowest values were coupled in the second, and so on across the range. The six amplitude-frequency pairs are listed in Table 1 and shown with the results in Figures 4 and 5. As with Experiment 1, each stimulus was comprised of 3 600-ms pulses of a sinusoidal signal.

Insert Figures 4 and 5 and Table 1 about here

Each of the 6 stimuli for a given condition was presented 3 times within a block of trials, within which the 18 values were randomly ordered. Subjects were pre-familiarized with the stimulus range before each block, as in Experiment 1.

3.2.2 Results and Discussion

The responses were normalized, log-transformed, and averaged as in Experiment 1. Figures 4 and 5 show the average log magnitude estimate as a function of the log stimulus value in the three conditions. For ease of comparison, the AM-FM data are duplicated in the two panels: they are shown together with the AM data, where amplitude is on the abscissa, and with the FM data, where frequency is on the abscissa.

The trends in the AM and FM conditions were comparable to those observed in Experiment 1, over the stimulus ranges that were manipulated in common across the two experiments (i.e., staying within frequency values that produced the monotonically increasing response range for the FM condition in Experiment 1). An ANOVA with the factors of stimulus level (6) and modulation condition (2) was performed to compare the AM-FM condition to each of the others. For the comparison with the AM condition, there were effects of stimulus level, $F(5, 55) = 124.61$, $p < .001$, modulation condition, $F(1,11) = 174.86$, $p < .001$, and the interaction, $F(5, 55) = 27.48$, $p < .0001$. For the comparison with the FM condition, there were also effects of stimulus level, $F(5,55) = 84.90$, $p < .001$, modulation condition, $F(1, 11) = 58.82$, $p < .001$, and the interaction, $F(5, 55) = 26.51$, $p < .0001$. The interactions indicate that the AM-FM data showed a significantly steeper trend than either of the component functions.

The slope of each function indicates the coefficient of a power function that would fit the non-log-transformed data. This coefficient indicates sensitivity to a given variable (Baird & Noma, 1978). The AM condition had a slope of 1.07, whereas the AM-FM function produced a slope of 2.43 with respect to amplitude variations. The FM function had a slope of 0.77, whereas the slope of the AM-FM function with respect to frequency variations had a slope of

1.63. Thus in both conditions, the slope more than doubled when amplitude and frequency were co-modulated, as opposed to modulated in isolation.

Note that the difference between the AM-FM condition and the others is observed predominantly for stimuli at the low end of the manipulated scale. This is an artifact of our design, since all three conditions shared a common value, representing the maximum frequency (300 Hz) and amplitude (2.5 V). Assuming no variation in perceived magnitude as a result of varying stimulus context, all conditions would be expected to meet at the common value, and variations across conditions would be free to occur at lesser values. It is also worth noting that the superiority of the AM-FM condition relative to the single-modulation conditions is greater when the single modulation is of amplitude rather than frequency. That is because the FM function departs from linearity to some extent, with the function becoming essentially flat near the maximum frequency. This is likely to derive from the inherent shape of the Pacinian corpuscle tuning function.

Supporting our conclusion that combined AM-FM modulation will strongly enhance sensitivity is work by Taylor (1977). He showed that co-varying the dimensions of amplitude (loudness) and frequency (pitch) improved performance in a simple speeded classification task more than when each dimension was used in isolation. He attributed the improved performance to the redundancy of the dimensions and suggested that loudness and pitch are integral dimensions, in the sense that they join together to form a single stimulus that is more discriminable than stimuli varied along one dimension alone.

3.3 Experiment 3: Multi-Finger Vibrotactile Summation

One may question why vibratory stimulation should be used to convey forces in a remote manipulatory environment, as opposed, for example, to auditory or visual feedback. One answer is that the vibratory stimulus can be applied differentially across multiple fingers, indicating the relative shape and contact point forces of the end-effector's grasp in relation to the object in the remote world. Another answer is that multiple fingers may be stimulated simultaneously, and summation across the fingers may enhance the sensitivity to the stimulus. It is this second advantage of vibrotaction that we investigate in Experiment 3; Experiments 4 and 5 deal with the use of multi-finger stimulation to indicate the geometry of grasping.

In relevant psychophysical work, Craig (1966) investigated the effect of stimulating multiple fingers with a vibrotactile signal of 60 Hz. Subjects were asked to adjust the amplitude of a standard vibratory signal, applied to the right middle fingertip, so as to match the amplitude of multi-finger stimulation on the left hand. The results indicated that multiple fingertip stimulation did increase apparent amplitude (loudness), but that the summation was not multiplicative: five stimulators on the left hand were needed to double the loudness of a single stimulator on the right. Another finding of interest was that the loudness functions were not affected by distance between the stimulators.

Experiment 3 measured the effects of multi-finger stimulation (from one to three fingers) and investigated whether the physical separation between the thumb and index finger influenced perceived signal magnitude. The present frequency range, from 50-300 Hz, goes well beyond that investigated by Craig (1966).

3.3.1 Method

The subjects were 11 individuals (5 male, 6 female) from the university community.

A voice coil was attached to each fingertip of the subject's right hand using velcro straps. The same assignment of specific voice coil to finger was held constant across subjects (with implications discussed in the results). Each coil could be activated independently. When multiple fingers were stimulated on a single trial, the same amplitude/frequency combination was applied to all fingers. The subject put his or her right hand on a support that separated the fingers so that vibrations could not be transmitted due to contact between them. As with the previous experiments, to ensure that the subject was unable to hear auditory cues from the miniature voice coil stimulators, he/she wore headphones playing white noise.

The task was again magnitude estimation, with the additional instruction that the subject should judge the intensity of the overall sensation and not focus on the number of fingers being stimulated. The 6 stimuli of the AM-FM conditions in Experiment 2 were used (see Table 1).

There were three conditions, corresponding to stimulation of 1, 2, or 3 fingers simultaneously. A total of 11 configurations was used. In the 1-finger condition, each of the 5 fingers was stimulated separately. In the other conditions where multiple fingers were stimulated simultaneously, a subset of the possible combinations was used in order to reduce the scale of the experiment. In the 2-finger condition (where 1 is the thumb and 5 is the last finger, the pairs 1-2, 1-3, and 2-3 were used. In the 3-finger conditions, the triads 1-2-3, 2-3-4, and 2-3-5 were examined. Because adjacent combinations of the 1, 2, and 3 fingers were used in all conditions, they allowed us to measure the effect of number of fingers across a common set of adjacent fingers. Comparison of two 3-finger combinations: 2-3-4 and 2-3-5 could be used to address the effects of finger separation.

The subject took part in a series of 198 trials, comprising 3 successive blocks of 66 trials each. Within each block, the 6 AM-FM signals were presented at each of the 11 finger configurations. The order of the 66 trials was randomized within each block. As with the previous experiments, the subjects were pre-familiarized with the stimulus range before each block.

3.3.2 Results and Discussion

The subjective magnitude estimates were normalized as in Experiments 1 and 2. Initial ANOVAs were performed on each condition, to assess the effects of individual finger or combination of fingers that were stimulated. These ANOVAs included stimulus level as a factor as well. Figure 6 shows the mean magnitude estimate for the single-finger condition in terms of signal amplitude; see Table 1 for the corresponding frequency. The analyses of the single-finger condition (where the finger that was stimulated was a factor -- see Figure 6) and the two-finger condition (where finger combination was a factor) showed significant effects of these factors, $F(4,40) = 3.52$, $p = .015$ and $F(2,20) = 3.84$, $p = .039$, respectively. However, the percentage of the total sum of squares that was attributable to these factors was very modest: 1.5% and 0.3%, respectively. In addition, because each finger had a consistently assigned voice coil, it seems likely that the effects of fingers are actually due to small differences in the stimulators themselves. Subsequent measurements of the stimulators' displacements revealed that those on fingers 2 and 4 had a displacement of –37 dB (ref. 1 mm/V) or 14 microns/V and the stimulator on finger 3 had a displacement of –41 dB or 8 microns/V; the latter stimulator tended to produce a slightly smaller magnitude than the others, consistent with the idea that voice-coil differences underlie the modest effects obtained. It should also be noted that the three-finger combination did not show a significant effect of particular finger combination ($F(2,20) = 2.64$, $p = .096$), contraindicating an effect of finger separation (recall that this condition included the 2-3-4 and 2-3-5 combinations). This agrees with Craig's (1966) null finding for finger separation.

Insert Figures 6-7 about here

The principal analyses were directed at the effects of number of fingers stimulated, in order to determine whether summation occurred. To perform these analyses, the data were grouped and averaged within each condition. Figure 7 shows the log magnitude estimates as a function of amplitude (see Table 1 for corresponding frequency) for the 1-, 2-, and 3-finger conditions. An ANOVA on stimulus level and number of fingers showed effects of stimulus, $F(5, 50) = 252.06$, $p < .0001$, and number of fingers, $F(2, 20) = 660.20$, $p < .001$. The interaction did not approach significance, $F<1$. All three functions were monotonic, and each had a slope of 1.16. When the log magnitude estimates were regressed against the log number of fingers stimulated (i.e., performing a regression on the three ordinate values for each abscissa value in Figure 7), the slope was 0.41 for each stimulus level, indicating that summation follows a power law rather than growing linearly (cf. Craig, 1966). As the stimulus intensity is increased, it results in a larger y-intercept, but the slope remains the same. Again, the lack of an interaction in the ANOVA indicates that summation across the fingers is independent of the stimulus intensity (coupled amplitude and frequency).

The finding that magnitude increases as a power of number of fingers stimulated contraindicates a loudness model for summation. That model assumes that loudness (i.e., perceived magnitude) sums across the fingers. That is, where L is the total loudness, n is the number of fingers, and L_f is the loudness at a single finger, then assuming that each individual finger is equivalent in response to the stimulator (i.e., all L_f values are equal),

$$L = \mathrm{Sum}(L1,...Ln) = n^* L_f \qquad (1)$$

This means that the ratio of loudness between two conditions would be equivalent to the ratio of number of fingers stimulated. Moreover, the loudness model would predict differential growth with number of fingers, depending on the stimulus magnitude; this is not observed.

An alternative model is summation of energy rather than loudness. The stimulus intensity can be viewed in terms of its energy, which is proportional to the square of the displacement (cf. voltage) amplitude and frequency (i.e., Energy = p * $\mathrm{Amplitude}^2$ * $\mathrm{Frequency}^2$ for some p). Others have shown that the perceived magnitude increases with approximately 0.5 power of the total vibratory energy for a single stimulation site (Marks, 1979; Verrillo & Chamberlain, 1972; Verrillo et al., 1969). An energy model would predict a power relationship between perceived magnitude and the total energy across the number of fingers stimulated with an exponent of 0.5. That is, where E is the total energy, n is the number of fingers, and $pA^2\omega^2$ is the energy at a single finger, then

$$E = npA^2\omega^2. \qquad (2)$$

This energy model would predict that to double the perceived magnitude over an observation made with a single finger, 4 fingers would have to be stimulated (with the same stimulus). Our plots of log magnitude and log number of fingers (see Figure 7) show a slope of 0.41 and if we extrapolate our data, 4 or 5 stimulators would be needed to double the perceived magnitude response. Both results are in fair agreement with the energy model prediction. In addition, these results agree with Craig's work with patterns of 60Hz vibration placed on fingertips and different locations on the body (Craig, 1966).

1.4 Summary of Psychophysical Experiments 1-3

These psychophysical experiments show considerable promise for the use of vibratory information at the fingertip, in order to convey forces in a remote environment. As we have mentioned, the use of vibration has a number of positive attributes. First, the locus of stimulation, being at the fingertip, is matched to the natural site of sensory response during direct manipulation (although the receptor populations that are stimulated by direct contact and vibratory stimulation are likely to be different). Second, the fingers can be differentially stimulated to indicate different forces that might arise, for example, during contact where the plane of the fingertips is not oriented parallel to the plane of a surface. Third, vibratory finger stimulation raises the possibility, which we have confirmed, of spatial summation, which potentially enhances the range of perceptual responses.

The miniature voice coils we have used in these experiments have been demonstrated to produce clearly discriminable perceptual responses, even within a single finger. The user was found to be sensitive to both AM and FM modulation. Moreover, when levels of amplitude and frequency were coupled, the effectiveness of the signal was considerably enhanced –in fact, more than doubled, where discriminability is measured by the slope of the log/log magnitude-estimation function (e.g., Klatzky & Lederman, 1999; Sherrick, 1985).

The experiments that follow will mount the voice coils within the fingers of a glove, by means of which the subject controls the movements of a remote, dexterous robot hand. The user receives vibratory feedback about the resulting forces in the remote environment. While the experiments we report are restricted to two-finger manipulation, the summation observed in Experiment 3 suggests that the application could readily be extended to multiple fingers.

4 Telemanipulation Experiments

This section discusses two telemanipulation experiments that were used to evaluate objectively the glove's effectiveness in conveying grasp force information to the wearer. From these tasks, we are able to show that proportional tactile feedback is helpful to a human operator performing remote manipulation tasks and that binary tactile feedback (which we used in our preliminary investigation) is not.

4.1 The Telemanipulation Testbed

Our vibrotactile glove may be used in several situations and applications, including telemanipulation. We have implemented a dexterous telemanipulation testbed to provide a realistic backdrop to evaluate the vibrotactile glove system (see Figure 8). This testbed consists of the four-fingered anthropomorphic Utah/MIT robot hand that is attached to a six degree-of-freedom manipulator (Puma 560), which moves the hand around in the workspace; this integrated element serves as the remote, slave system. The human operator wears a CyberGlove™ to measure finger motions and a Polhemus ISOTRAK™ system to measure the operator's wrist position; this master system is used to drive the remote system in the workspace to manipulate objects. The force exerted on an object by the robotic hand is measured using calibrated force sensitive resistors (FSRs) that are attached to each fingertip of the robotic hand. This force information is conveyed to the human operator via the vibrotactile glove; this enables a human operator to “feel” the forces exerted on an object as he/she manipulates it via the remote system.

This telemanipulation system runs under the Chimera real-time operating system (Stewart et al. 1992) that provides the necessary computational speed such that the remote system is able to mimic the operations motions effectively. The accuracy of the mapping from human wrist movement to the manipulator wrist is within 1.1 mm, and the latency of the manipulator wrist movement is approximately 0.1 seconds. Providing an accurate correlation from the user’s finger motions to the robot fingers is difficult since it is not a one-to-one mapping; the number of fingers, the length of the finger segments, and the range of motion for the joints are different for the robot hand and a human hand. We used a calibration routine to provide the best qualitative correlation possible. The human-to-robot finger motion latency is 0.15 seconds.

4.2 The Vibrotactile Glove’s Stimuli

For our telemanipulation experiments, we want to convey continuous touch and force information from the remote task to a human operator via the vibrotactile glove. We achieve this goal by co-varying the voice coil’s signal amplitude and frequency. The wearer’s response to the co-modulated vibration is non-linear (see Section 3.2), but we want the wearer’s perceived intensity of the vibration to be proportional to the manipulation force. To do this, we scale the measured forces to the magnitude estimate range found in Experiment 2, so that a force in the robotic environment can be assigned a magnitude estimate within the experimentally obtained range; we then use the inverse of the power-law function determined from our psychophysical experiment (i.e., the magnitude estimate vs. correlated signal amplitude and frequency) to compute the desired amplitude and frequency of the vibration signal for a given magnitude estimate (which is related to a measured force). In each of the experiments we present below, this type of mapping is used to produce a proportional touch force feedback such that the perceived intensity of the vibration is in proportion to the forces measured in the remote environment.

Our approach requires that the human operator not only perceives discriminable levels of vibration, but that he/she translates these signals into an internal representation of grip force that at least preserves a monotonic relation between the continua. Our experiments do not address the nature of this translation, e.g. whether the operator uses a cognitively mediated rule or cross modal matching at a perceptual level (Marks, 1982). However, the experiments do address the efficacy of the translation, since if processing cannot be done quickly and with reasonable preservation of the force continuum, the tasks will not be performed adequately.

4.3 Experiment 4: Adaptive Force-Limited Pick-and-Place Task

The objective of this experiment is to compare different forms of feedback (vision with no tactile feedback, vision with binary tactile feedback, and vision with proportional tactile feedback) presented to a human operator while he/she is performing a pick-and-place task within the constraint of a target grip force range.

4.3.1 Method

Twelve right-handed individuals (9 male, 3 female) from the university community participated in this experiment.

Each subject teleoperated the dexterous robotic hand to pick up a block, using a thumb-index finger pinch grasp. The objective was to pick up the block without triggering a yellow warning light, which indicated excessive grip forces (see Figure 8).

Insert Figure 8 about here

What the subject did not realize was that the force threshold for the warning light -- called the overgrip threshold -- was adapting to his/her performance. The overgrip threshold is a multiple of the minimum grip force needed to successfully lift the block (determined as described below). For the first trial of each feedback condition, the threshold was set to a multiple of 2.25 (i.e., 2.25 * minimum grip force). If the light flashed four trials in a row for the same feedback condition, the overgrip threshold was increased by 0.3 to make the remaining trials easier for the subject (the threshold's upper limit was 3.5 to protect the robotic hand from possible damage). When the subject had two consecutive successful trials without the light flashing in the same feedback condition, the overgrip threshold was decreased by 0.1. These multiplicative factors were tracked for each feedback condition; they indicated how well the subject was able to use the different forms of feedback in this task.

One of two blocks was used in a trial: a heavy block (700 g) marked with an “H” or a light block (210 g) marked with an “L”. The gripping surface of the block was covered with rubber to give a less abrupt change in force as the subject gripped the block. An estimate for the minimum grip force needed to lift each block was determined experimentally by picking up the block and slowly releasing the grip between the robot's thumb and index finger until it dropped. The value immediately prior to the drop indicated the minimum force needed to pick up the block successfully. The minimum grip force for the heavy block was 5.9N per finger; and for the light block, 1.7N per finger.

Three tactile feedback conditions, in combination with vision, were considered in this experiment: no feedback; proportional feedback; and binary feedback. Visual feedback consisted of a monocular, shoulder-angle view of the robotic hand and worksite. Tactile feedback, if present, was provided by two voice-coil stimulators: one attached to the thumb fingertip and one on the index fingertip of the subject.

For the proportional tactile feedback condition, the voice coils' signal amplitude and frequency were co-varied to convey force to the user as discussed in Experiments 2 and 3 (see Table 1). The vibration of the voice coil stimulator was modulated continuously (from 0.76 V signal amplitude at 50 Hz to 2.5 V signal amplitude at 300 Hz), corresponding to a grip force range of 50 g to 2100 g.

The binary tactile feedback condition was similar to that used in our preliminary investigation, where the tactile stimulators remained off until the forces applied by the robot's fingers reached a desired fixed threshold. When the force threshold was reached, the tactors turned "on" and vibrated at a constant frequency and amplitude. For this experiment, the miniature voice coils vibrated at 250 Hz with a 2.4 V signal amplitude (displacement is 40 μm); this frequency maximally excited the Pacinian corpuscles and 2.4 V produced a large, suprathreshold displacement. The threshold force in this condition was set at the minimum force needed to lift the block successfully.

At the beginning of the trial the subject placed his/her hand on a platform. The experimenter placed the target block in a white frame on the table, which restrained its motion and made capturing the block easier for the subject. The letter on the block, indicating its relative weight, was placed up for the subject to see. The subject wore headphones playing white noise to eliminate any possible acoustic cues from the pneumatics of the robotic hand or from the miniature voice coil tactors. The start of the trial was indicted by the experimenter with a hand-motion, since the subjects could not hear.

Each subject in this experiment performed two sets of 48 trials, each divided into three subsets corresponding to the three feedback conditions. Eight trials with each block (heavy vs. light) were presented, in random order, while a feedback condition was held constant, and the order of the feedback conditions within each 48-trial set was varied across subjects using a Latin Square design. The overgrip threshold for each of the feedback conditions at the end of the first set of trials was used as the starting point for the second set. The experiment took a subject 2-2.5 hours to complete, with a 10-minute break between the sets.

Prior to the start of the experiment, the subject was allowed to practice picking up random objects placed on the table (e.g., a miniature football, a softball, and a block). This allowed him/her to learn how to use the system and gave the experimenter a chance to tune the Cyberglove™ mapping from the subject's hand to the robotic hand. The subject was allowed to practice until he/she felt comfortable with the testbed, which typically took 20-30 minutes.

1.1.2 Results and Discussion

Several types of data were available from this experiment. During each trial the system sampled, at 100 Hz, the feedback status (on/off for the binary condition; or proportional value), the force on each robot finger, the robot's wrist position (desired and actual) and hand joint positions; and the user's finger joint positions and wrist position. Also recorded for each trial was the current value of the threshold for the warning light (overgrip threshold) (see Figure 9). From these data, we calculated several aggregate performance measures over trials, which were computed for each block weight and feedback condition. These included the total number of errors (overgripping or dropping due to undergripping), the task completion time, the maximum overgrip threshold, and the final value of the overgrip threshold (i.e., the value on the last trial).

Insert Figure 9 about here

The grip force was evaluated both as a total across fingers and for the finger with the largest grip-force reading. The single-finger measure was used to account for trials in which the subject grabbed the block on its edge, producing widely discrepant force readings between the thumb and index fingers. Direct performance comparisons between the heavy and light blocks were made possible by dividing the measured grip force by the minimum force needed to lift the particular block successfully. The resulting metric is called the "grip force ratio". The mean, maximum, and variance of this ratio -- computed over only those intervals where the grip force was non-zero -- were used as aggregate performance measures. The various force measures were determined over the trial as a whole and during the period where the object was lifted. The lift of the block was isolated by using the robot's X and Z position data (see Figure 9). A lift was marked by an increase in the robot hand's Z position followed by a decrease in Z, while the hand remained at a relatively constant position in X. If there were multiple lifting attempts in a trial, only the last attempt (i.e., completed lift) was used.

Figures 10 and 11 show representative force data: the mean grip force ratio for the finger with largest force, during the lift and for the whole trial, the maximum grip force ratio for the same finger across the trial, and the variance of the total grip force ratio (all fingers) during the whole trial. Other force measures show similar trends and are omitted for brevity. All are shown by block type (heavy, light), trial set (first half, second half), and tactile feedback condition (none, binary, and proportional).

Insert Figures 10 and 11 about here

For all of the grip force measures, we see three pervasive trends in the data. First, the subjects used a larger grip force ratio for the light block than the heavy block. This was not surprising, since given the difference in the required force to prevent slip of the light and heavy blocks, less force was needed with the light block to produce large changes in the grip force ratio. As a result, maintaining a consistent grip ratio required a more precise regulation of grip forces for the light block than it did for the heavy block. A second trend in these data was for the grip force ratio to be greater for the first half than for the second half of the trials. So, for both block types and across all feedback conditions, the subjects' performance improved as the experiment progressed. Although the subjects improved in their ability to regulate the grip forces, the mean finger grip ratio they used while lifting the blocks was larger than that used in barehanded manipulations. Extensive research by Johansson and Westling show that we use a grip ratio of approximately 1.5 in bare-handed lifting, regardless of the weight and the grip surface properties

(Johansson & Westling, 1984; Westling & Johansson, 1984). Our results may be due in part to the vibrotactile nature of the display (i.e., it is not transparent).

A third trend in the data became more apparent through the statistical analysis , which indicated significant differences between the feedback modes' grip force ratios. With proportional tactile feedback, the subjects were able to use smaller grip forces and control the grip forces significantly better than they could with the binary feedback or with no tactile feedback (e.g., for mean grip force ratio: $F(1,9) = 14.65$, $p = 0.004$ for Binary vs. Proportional Feedback contrasts, and $F(1,9) = 4.31$, $p = 0.07$ for No-Feedback vs. Proportional Feedback contrasts). There was no significant difference in performance between the no-tactile-feedback and the binary-tactile-feedback modes. This analysis suggests that the performance (according to the mean, maximum, and variance of the grip force) was worst with the binary tactile feedback, slightly better with no tactile feedback, and best with the proportional feedback.

In Figure 12 we show the overall error rate (i.e., average number of errors per trial) and task completion time for each block, feedback condition and half of trials. Two types of errors were monitored in each trial: overgripping the block (i.e., the overgrip threshold light was activated) or dropping the block (due to undergripping). A maximum of two errors could occur in a trial: the trial was not terminated when the overgrip warning light was triggered, but was terminated if the subject dropped the block. The most common type of error was overgripping the block (relatively few errors were committed by dropping the block). The overall error rate shows that the lighter block was noticeably harder to pick up without triggering the overgrip threshold for all feedback conditions ($F(1,9) = 89.07$, $p = 0.0001$). As we discussed for the mean, maximum, and variance of the grip force ratio data, the lighter block required a finer control of the grip forces to maintain a legal (i.e., non-overgrip) grip force ratio; as a result, the overgrip threshold light was triggered more often. For both block weights, the subjects learned how to reduce their number of overgrips by the second half of the experiment: they decreased their grip forces ($F(1,9) = 9.98$, $p = 0.01$). For task completion time, we see a discernible decrease from the first half to second half of the trials for all feedback conditions ($F(1,9) = 16.43$, $p = 0.003$); however, there were no significant differences among the different feedback modes.

Insert Figure 12 about here

The overgrip threshold succinctly captured the governing trends in the data we saw with the mean, maximum, and variance of the grip force ratio data and the error rate data. In Figure 13 we show the progression of the adaptive threshold values (as a multiple of the minimum force needed to prevent slip) during the experiment for each subject and feedback condition. The experiment began with a low threshold, which generally rose due to overgripping and subsequent increase of the tolerated force. This continued until the subjects mastered the grip, at which point the adaptive procedure made the task more difficult by lowering the overgrip threshold. For all conditions, we see that most of the subjects reach a peak threshold force ratio by the fourth or fifth trial group (between trials 16 and 20). After reaching this peak value, the subjects with proportional feedback then improved over the remaining trials; with no tactile feedback some subjects improved their performance and a few showed little or no improvement; with binary tactile feedback over half of the subjects showed little or no improvement. An ANOVA revealed that the peak value for overgrip threshold ratio was significantly different among the feedback modes ($F(2,18) = 12.09.95$, $p = 0.0004$). The maximum overgrip threshold value (i.e., maximum across trial groups) with proportional tactile feedback (subject average = 2.92) was noticeably less than the no-tactile-feedback maximum (subject average = 3.12) and binary feedback maximum (subject average = 3.20). There was no statistically significant difference between the binary and the no-tactile-feedback condition. This trend was also evident in the final value for the overgrip threshold. Again, we saw significantly better performance with the proportional tactile feedback (subject average = 2.72) than we did with the other two feedback modes (binary subject average = 3.10, and no feedback subject average = 3.00) ($F(2,18) = 13.52$, $p = 0.0003$). Both overgrip threshold measures indicate that the proportional feedback allowed the subjects to control the grip forces more effectively than they could with the other two modes of feedback.

Insert Figure 13 about here

Through objective measures we have demonstrated quantitatively that using proportional tactile feedback yields significant performance benefits over binary and no tactile feedback when controlling grip forces is critical to the success of the task. With proportional tactile feedback, the subjects were able to regulate the peak, average, and variance of the grip forces better; this resulted in a lower overgrip threshold, which adapted to the subjects' performance. The favorable performance with proportional tactile feedback was the result of continuous and timely flow of interpretable touch and grip force information to the subjects. The majority of subjects all reported that they thought the proportional feedback was more helpful and informative than the other feedback modes.

Between the remaining two feedback modes, the subjects performed slightly better with no tactile feedback than they did with the binary tactile feedback. With binary feedback, the subjects used greater grip forces, resulting in the highest overgrip threshold (maximum value and final value). When the minimum grip force was reached, the binary feedback turned "on" and continued to vibrate at a constant frequency and amplitude until the forces dropped below the minimum force. Thus, after the binary feedback was activated, no additional information was provided about the grasp progress. Many subjects reported that they found the binary feedback annoying, abrupt, and misleading. The subjects' opinions were almost evenly split on whether binary feedback was better than no tactile feedback. This notable finding has helped us to refine our conclusions from our preliminary investigation (Murray et al., 1997) with binary SMA tactile feedback: the binary nature of the feedback mode was a significant contributing factor in the degradation in operator performance.

1.2 Experiment 5: Sorting Objects by Relative Weight

In this experiment, we measured the ability of the human operator to sort three blocks according to their relative weight, using visual feedback alone (no tactile feedback) or using both visual and proportional tactile feedback. We anticipated that the proportional feedback would be highly useful in this task, because subjects could use it to determine the relative force needed to prevent slip, and from this infer the weight of the block.

1.2.1 Method

Ten right-handed subjects (8 male, 2 female) from the university community participated in this experiment.

The subject teleoperated the robotic hand to pick up each of three blocks sitting on the table, using a thumb-index finger pinch grasp. The goal was to determine the relative weights of the blocks (e.g., light, medium, and heavy) by lifting and comparing them as many times as necessary to help make a decision (see Figure 14). The blocks looked identical, but each had a different weight: 210 g, 465 g, and 700 g. The subject was told that one block was “light”, one was “heavy”, and one was “in-between” or “medium”.

Insert Figure 14 about here

Two feedback conditions were used in this experiment: vision with no tactile feedback, and vision with proportional touch feedback. The visual feedback was similar to that in the first experiment, but the contrast on the video monitor was turned down so the subject could not see any identifying marks on the blocks, differences in their surfaces, or other tell-tale visual cues. The proportional tactile feedback was identical to that described in the preceding experiment.

At the beginning of the trial the subject placed his/her hand on a platform. The three blocks were placed in a row on a table near the robotic hand while the subject’s view was obstructed. As in the preceding experiment, the subjects were wearing headphones playing white noise and the start of the trial was indicated with a hand motion from the experimenter. Then the subject reached over and picked up each of the blocks as many times as needed to make a weight-ranking decision. The most common strategy used by a subject in the experiment was to adjust his/her grasp on the block until he/she was just able to lift the block and then gauge the grip force used in order to determine the relative weight of the block (the subject was instructed not to drop the block). When he/she had come to a decision, the subject placed his/her hand back on the platform and told the experimenter the order of the blocks. The experimenter then told the subject the correct order of the blocks. The correct order and the order given by the subject were recorded.

Each subject completed 30 trials. The trials were evenly split between the two feedback conditions and were randomly presented in the experiment. The experimenter indicated to the subject the type of feedback to be presented in the trial by holding up a sign. The order of the blocks was also randomly chosen for each trial in the experiment.

Prior to the start of the experiment, the subject was allowed to practice picking up random objects on the table to become familiar with the system. After the completion of the experiment, the subject was allowed to examine and lift the blocks directly with his/her hands.

1.2.2 Results and Discussion

The correct block order and the subjects' responses were compiled to form an overall confusion matrix for all of the subjects (see Tables 2a and 2b) In the confusion matrix, the columns show the block presented (i.e., the stimulus presented) and the subjects' responses are tallied along the rows. The on- diagonal terms represent the number of times the subjects were able to correctly identify the relative block weight (i.e., correct classification). The off-diagonal terms represent the number of times the subjects incorrectly identified or confused the relative block weight (i.e., incorrect classification). Each block was presented a total of 150 times (15 three-block trials per subject) for each feedback condition. Thus, a score of 150 along the diagonal terms would indicate perfect identification of the blocks across all subjects.

Insert Table 2 about here

For the no-tactile-feedback condition, the off-diagonal elements show that the subjects confused the medium block equally often for the light and heavy blocks, but were less likely to confuse the light and heavy blocks. The on-diagonal elements for no tactile feedback are less than those for the tactile feedback condition, indicating the subjects performed the task better with feedback. For the tactile feedback condition, the subjects were most likely to confuse the medium and heavy blocks and least likely to confuse the light and the heavy blocks.

A paired t-test was performed across feedback conditions on the number of trials with error and the total number of errors each subject had in the experiment (note that the minimum number of errors per trial is two, as two blocks must be switched). Each t-test showed significant performance gains for proportional feedback versus no tactile feedback: for the number of trials with an error $t(9) = 4.13$, $p = 0.0026$; and for the total number of errors committed $t(9) = 3.47$, $p = 0.007$. To determine if there were performance differences across the block types, we considered the correct results for each block type as a binomial distribution with 95% confidence intervals, which is commonly used in pattern recognition applications. However, we ignore the fact that a confusion error means that in confusing block A with block B, both A and B must produce an error, thus errors are not entirely independent. This method illustrates that proportional feedback was better than no feedback for helping the subjects distinguish the light and medium blocks. With proportional feedback, the subjects showed an accuracy of 82.7% for the light block (with 95% confidence bounds of +6.2% and –6.6%) and 70% (+7.61, -7.8) for the medium block. In contrast, the subjects demonstrated an accuracy of 61.3% (+8.11, -8.2) for the light block and 46% (+8.3, -8.3) for the medium block when no tactile feedback was used. For the heavy block, however, proportional feedback had only a marginal gain in performance over no tactile feedback. The subjects were able to correctly identify the heavy block 76% (+7.0, -7.3) of the time with proportional feedback and 66.7% (+7.8, -8.0) of the time without feedback. Anecdotal reports from the subjects suggest that they sometimes were able to distinguish the heavy block by its twist or droop when lifted; this helped them in performing the task without tactile feedback. Also, the trend in the data across feedback conditions shows that the medium block was misidentified more often than either the light or heavy block.

This experiment has helped to illustrate that proportional vibrotactile feedback is useful in helping subjects distinguish relative object properties such as weight. The results and analysis provide strong evidence that the vibrotactile glove's proportional tactile feedback is superior to no tactile feedback in the task considered. Determining how much information was transferred to the subjects with the tactile feedback was not the intent of this experiment, since too few trials were conducted and too few independent "choices" were considered to get a reliable information transfer measurement (Tan, 1996). However, using the data we collected, we can determine a *rough* estimate of the information transfer if we consider the order of the blocks as a pattern or choice. To estimate the number of bits of information observed by the subject (known as mutual information in information theory), a weighted sum of the occurrence of joint stimulus and response event is taken as follows:

$$I_{transmitted\_estimate} = \sum_{r=1}^{6}\sum_{s=1}^{6}\frac{n_{rs}}{N}\log_2\left(\frac{n_{rs}\bullet N}{n_r\bullet n_s}\right) \tag{3}$$

where N is the total number of trials conducted in the experiment, n_{rs} is the number of times the event response r from stimulus s occurs, n_r is the total number of times the response occurs, and n_s is the total number of times the stimulus occurs in the experiment (e.g, Cover & Thomas, 1991). With tactile feedback, the estimated information transmitted in this experiment is 1.27 bits and without tactile feedback 0.65 bits. The maximum information that could possibly be transmitted to the subject was 2.58 bits ($\log_2 6$). The non-zero information rate, when no tactile feedback was used, suggests that information was indeed conveyed by other means such as visual cues. Even with this rough approximation, we show that tactile feedback conveys more information that no tactile feedback.

2 Conclusion

In this paper we have described a series of experiments with a vibrotactile glove to demonstrate the potential of using vibratory information at the fingertip to convey interactive forces in a remote environment. The three psychophysical experiments provided the foundation for determining the user's sensitivity to the glove's tactile stimulation and for defining the vibrotactile glove's operating range. The results of Experiment 1 showed that the vibrotactile stimulator (i.e., a commercially available miniature voice coil) is capable of producing perceptible differences in stimulation when the frequency or signal amplitude of the stimulator are varied. Experiment 2 expanded this work further and demonstrated that coupling changes in the vibration's frequency and amplitude almost doubled the user's sensitivity to the vibrotactile stimulation. In Experiment 3, we showed that spatial summation occurs when multiple fingers are stimulated with a vibratory stimulus simultaneously, but the gain is by diminishing returns.

The telemanipulation experiments we have described were designed to objectively measure the usefulness of the vibrotactile glove in a realistic teleoperation environment. In these experiments, the user received vibratory feedback about the grip forces of a multi-finger robotic hand in the remote environment. Both experiments examined the ability of a user to regulate grip forces using the vibrotactile feedback. In Experiment 4, the subjects performed a pick-and-place manipulation task where the grip force needed to be controlled to lift an object of known relative weight without overgripping it. From this work, we have shown that proportional vibrotactile feedback out-performs binary feedback and no tactile feedback in terms of objective measures, such as the mean, peak, and variance of grip forces. Additionally, we have shown that binary feedback produced the worst user performance and was actually worse than having no tactile feedback at all.

In Experiment 5, we reversed the task by having the user sort objects by weight using the vibratory feedback. The user performed this task by adjusting his/her grip forces to lift the object and interpret the vibratory feedback intensity when it was provided. From this experiment, we have shown that users could translate the vibratory stimulation to judgments of relative weight. Other properties that it could help to extract are compliance, first approximation of surface roughness, or size and shape (via touch alone). Both telemanipulation experiments have shown that proportional vibratory feedback is significantly more effective (in terms of objective measures such a mean grip force) than performing the same tasks without tactile feedback.

It should be emphasized that the vibrotactile technology that was investigated here is not only effective, but inexpensive and available in off-the-shelf products. No doubt, vibrotactile interfaces will increasingly be found in human-computer interaction. A vibrotactile mouse, which is commercially available, is likely to be highly useful in applications where relative force is to be conveyed, even though it does not provide stimulation to the individual fingers as does the vibrotactile glove. Applications of the mouse, for example, could include telemanipulation in a planar environment, where the plane maps to the user's screen. Conveying the relative values of properties of objects like weight in virtual environments would also be possible through vibratory stimulation to the whole hand. The present research is a first step in demonstrating the effectiveness of this technology and identifying potentially useful domains of application.

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Table 1. Stimulus Levels for sinusoidal excitation of the voice coil display used in Experiments 2 and 3 when co-varied AM/FM stimuli were used.

Table 2. Confusion matrices for the sorting experiment of 150 trials. (a) No-tactile-feedback condition; (b) Proportional tactile feedback condition.

Figure 1. The vibrotactile glove system with the miniature voice coils (i.e., small audio speakers) shown attached to the fingertips.

Figure 2. The average of subjective magnitudes (with standard errors) for vibrotactile stimuli from a 250Hz sinusoid at different amplitudes. The associated loaded displacement of the stimulator is also shown on the top. After Murray, Klatzky, & Khosla (1998).

Figure 3. The average subjective magnitudes (with standard errors) for vibrotactile stimuli from a suprathreshold sinusoid at different frequencies. The associated loaded displacement of the stimulator is also shown on the top. After Murray, Klatzky, & Khosla (1998).

Figure 4. The average subjective magnitude estimates (with standard errors) for both the AM condition and the combined AM-FM condition. The associated loaded displacement of the stimulator is also shown on the top. After Murray, Klatzky, & Khosla (1998).

Figure 5. Average subjective magnitude estimates (with standard errors) for both the FM condition and the combined AM-FM condition. The associated loaded displacement of the stimulator is also shown on the top. After Murray, Klatzky, & Khosla (1998).

Figure 6. The mean magnitude estimates with standard error bars for one finger stimulation at the six stimulus levels, in terms of signal amplitude (1 volt referenced to approximately 14

mm loaded displacement) (see Table 1 for signal frequency). After Murray, Klatzky, & Khosla (1999).

Figure 7. The mean magnitude estimates with standard error bars for the finger groups at each of the six stimulus levels, relative to signal amplitude (1 volt referenced to approximately 14 mm loaded displacement) (see Table 1 for signal frequency). After Murray, Klatzky, & Khosla (1999).

Figure 8. An overview of the force-limited pick-and-place experiment: (a) the remote site setup; (b) the human-operator's work site with the subject ready to begin the trial; (c) the human operator reaching over to pick up the selected block at the remote site; (d) the robot grabbing the block.

Figure 9. A time history of a trial in the force-limited pick-and-place experiment (binary feedback mode). Upper panel: Dashed line is index finger force; solid line is thumb force; threshold forces for fingers and overgrip are also shown. Middle panel: State of flags (on/off) for the index and thumb exerting force and the overgrip threshold being passed. Lower panel: Robot wrist position along the x and z axes.

Figure 10. Subject averages and standard errors of the mean finger grip ratio for each tactile feedback condition and block weight (top: non-zero data averaged for an entire trial; bottom: data averaged during lift phase only). The data are averaged separately over the first half and second half of the experiment.

Figure 11. Subject averages and standard errors of the maximum trial finger grip ratio and variance of the finger grip ratio for each tactile feedback condition and block weight. The data are averaged separately over the first half and second half of the experiment.

Figure 12. Subject averages and standard errors for the number of errors occurring per trial (error rate) and for task completion time for each tactile feedback condition and block weight. The data are averaged separately over the first half and second half of the experiment.

Figure 13. The progression of the overgrip force threshold ratios (shown in eight 4-trial blocks) through the experiment for each subject and tactile feedback condition. Each symbol represents the same subject in each feedback condition.

Figure 14. An overview of the sorting experiment: (a) shows a front angle view as the robot hand is teleoperated to pick up one of the three blocks; (b) shows a side view of the task.

Table 1. Stimulus levels for sinusoidal excitation of the voice coil display used in Experiments 2 and 3 when co-varied AM/FM stimuli were used.

Stimulus Level	**Amplitude - Volts** (Displacement - μm)	**Frequency-Hz**
1	0.76 (10.1)	50
2	1.11 (16.4)	100
3	1.43 (20.9)	150
4	1.78 (26.8)	200
5	2.13 (35.1)	250
6	2.5 (53.8)	300

Table 2. Confusion matrices for the sorting experiment of 150 trials. (a) No-tactile-feedback condition; (b) Proportional tactile feedback condition.

(a)

WITHOUT TACTILE FEEDBACK

SUBJECT RESPONSE \ STIMULUS	Light	Medium	Heavy
Light	**92**	**41**	**17**
Medium	**48**	**69**	**33**
Heavy	**10**	**40**	**100**

(b)

WITH TACTILE FEEDBACK

SUBJECT RESPONSE \ STIMULUS	Light	Medium	Heavy
Light	**124**	**17**	**9**
Medium	**18**	**105**	**27**
Heavy	**8**	**28**	**114**

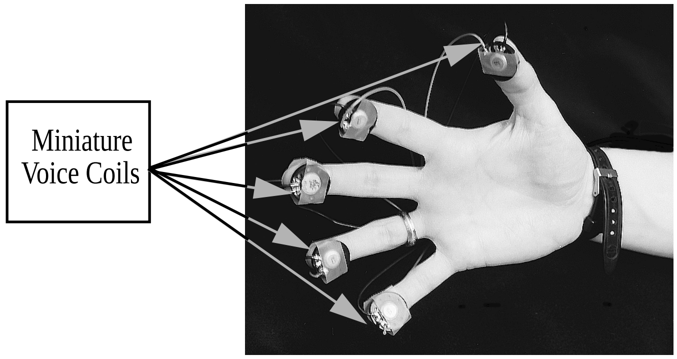
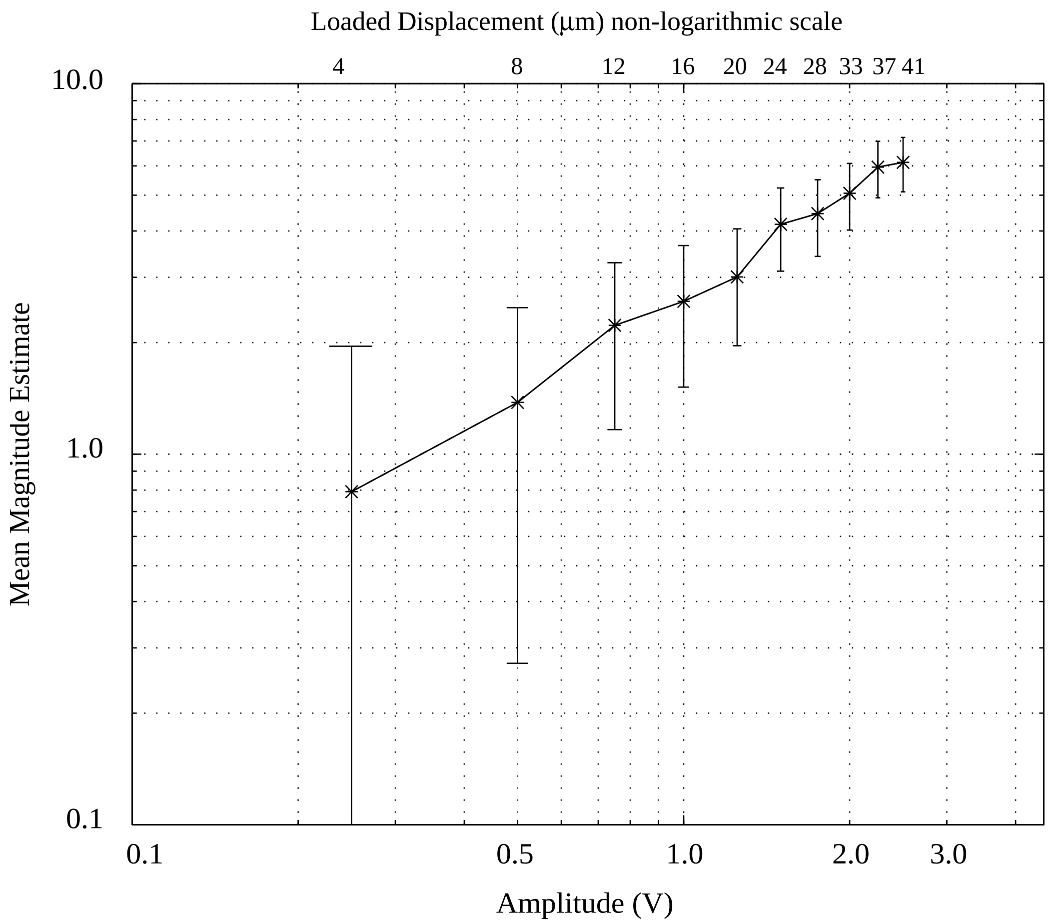


Figure 1. The vibrotactile glove system with the miniature voice coils (i.e., small audio speakers) shown attached to the fingertips.



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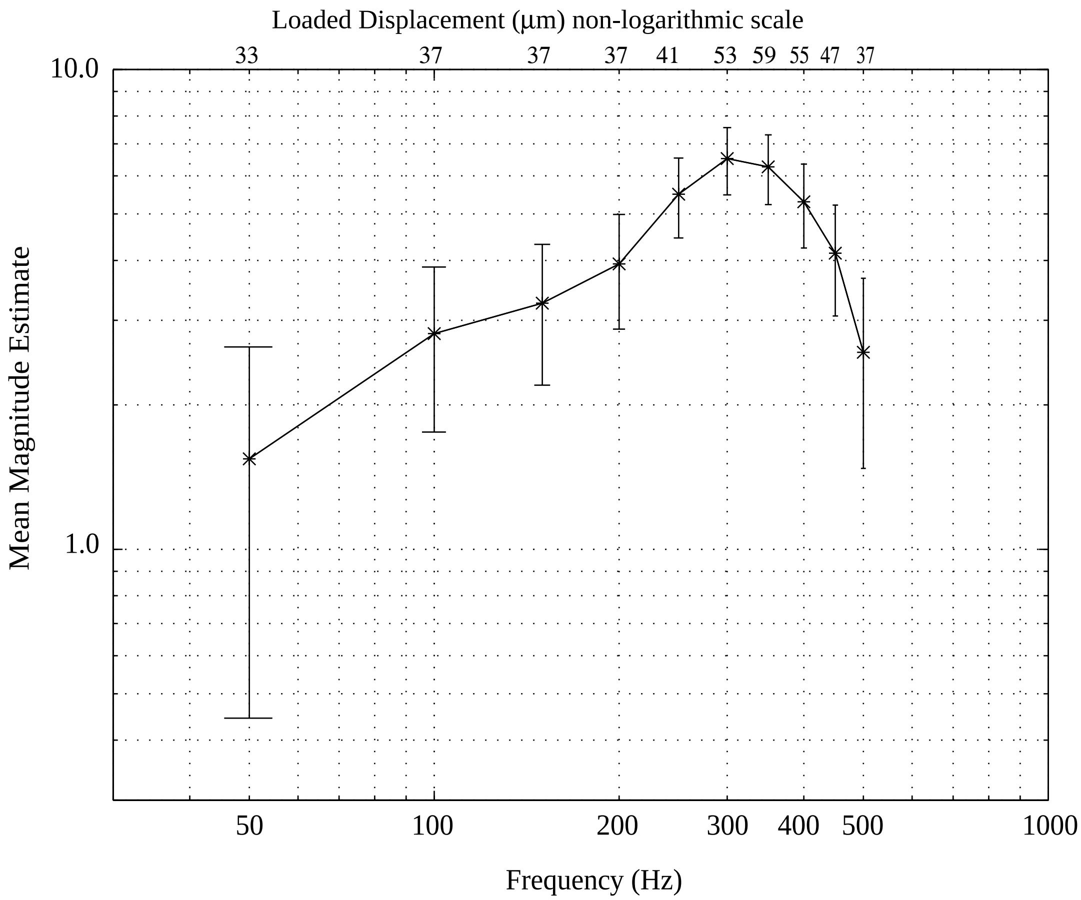
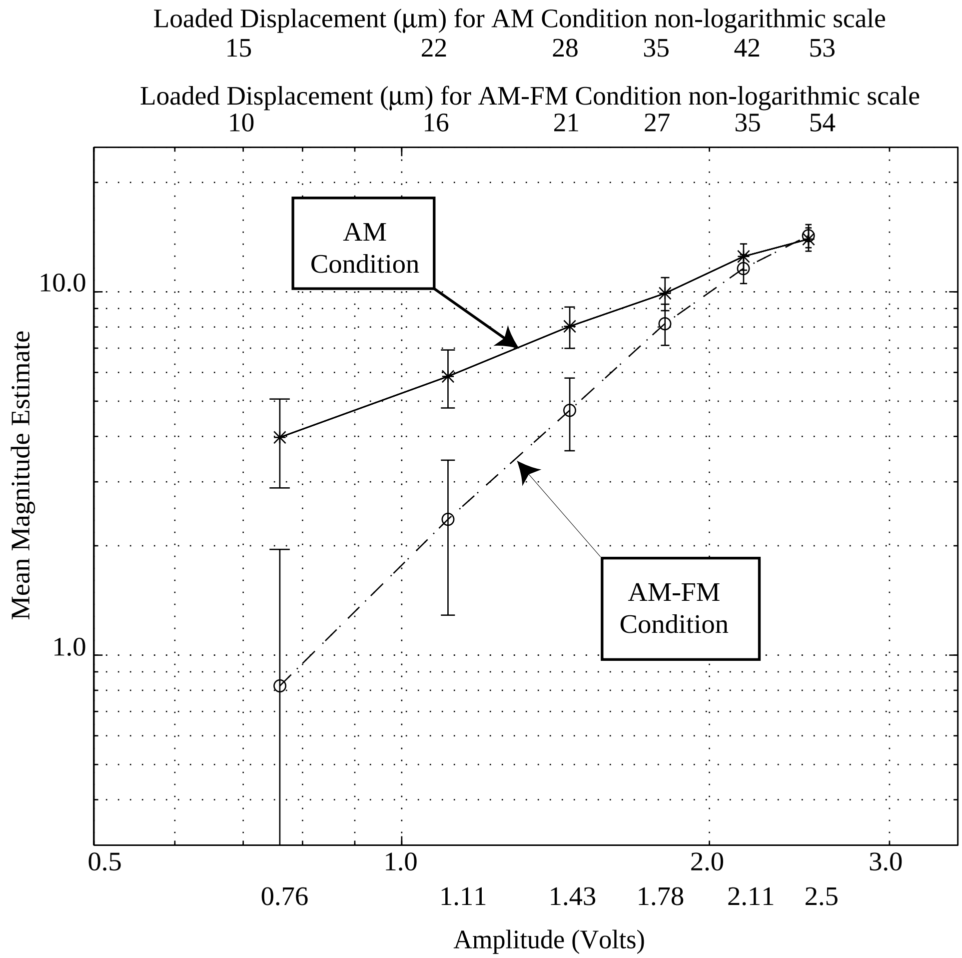


Figure 3. The average subjective magnitudes (with standard errors) for vibrotactile stimuli from a suprathreshold sinusoid at different frequencies. The associated loaded displacement of the stimulator is also shown on the top. After Murray, Klatzky, & Khosla (1998).



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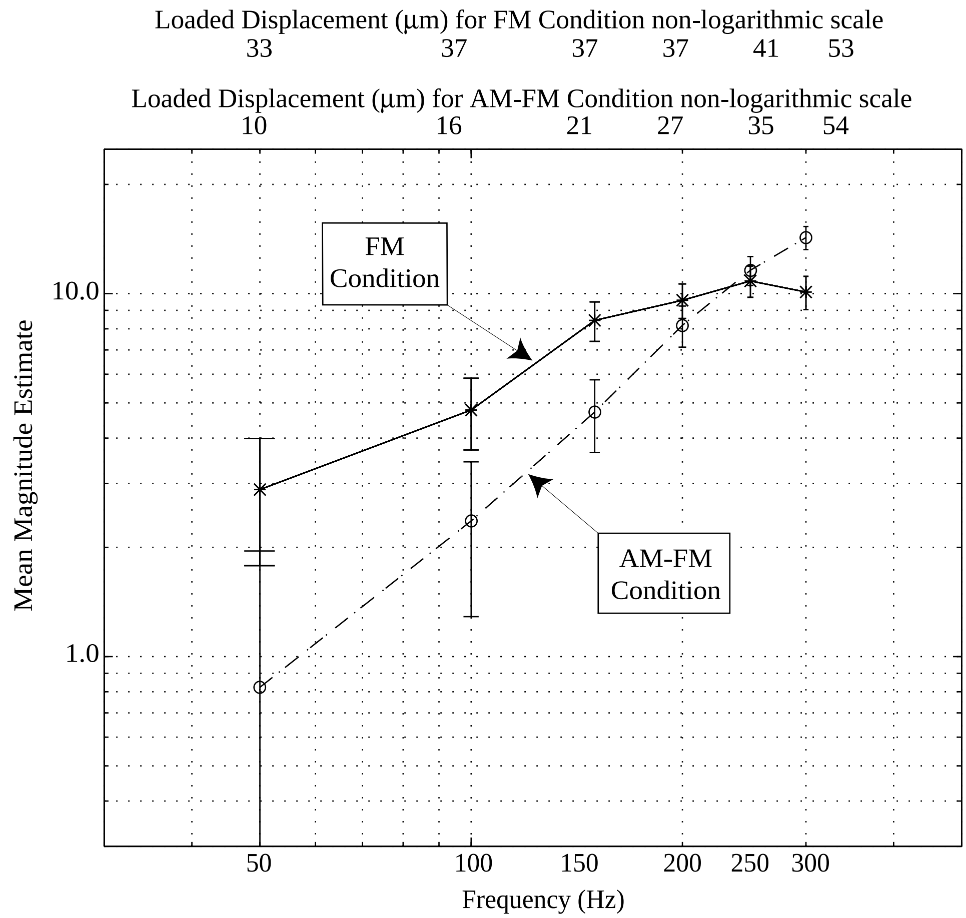
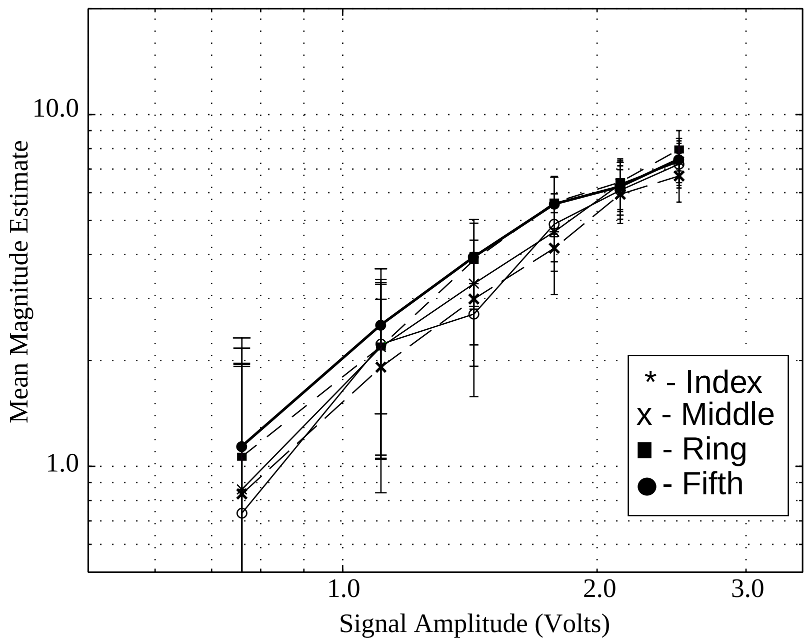


Figure 5. Average subjective magnitude estimates (with standard errors) for both the FM condition and the combined AM-FM condition. The associated loaded displacement of the stimulator is also shown on the top. After Murray, Klatzky, & Khosla (1998).



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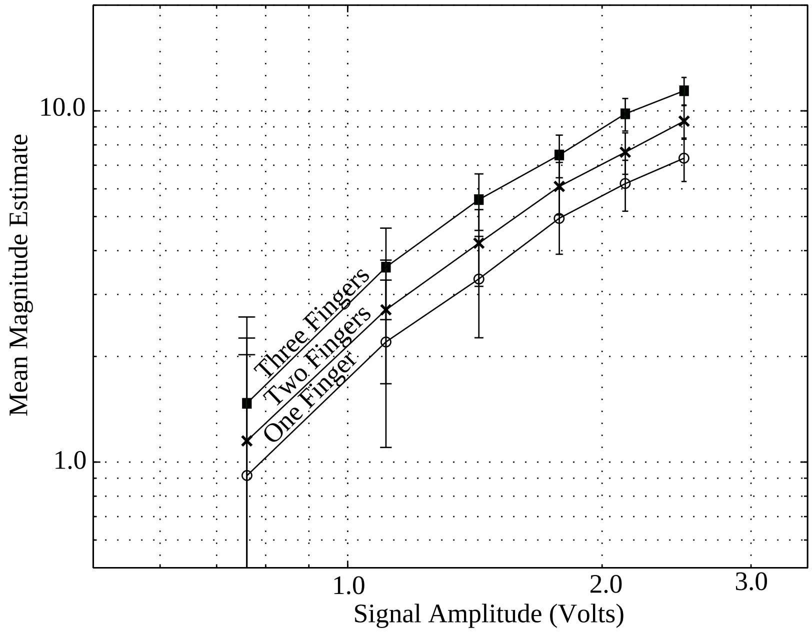
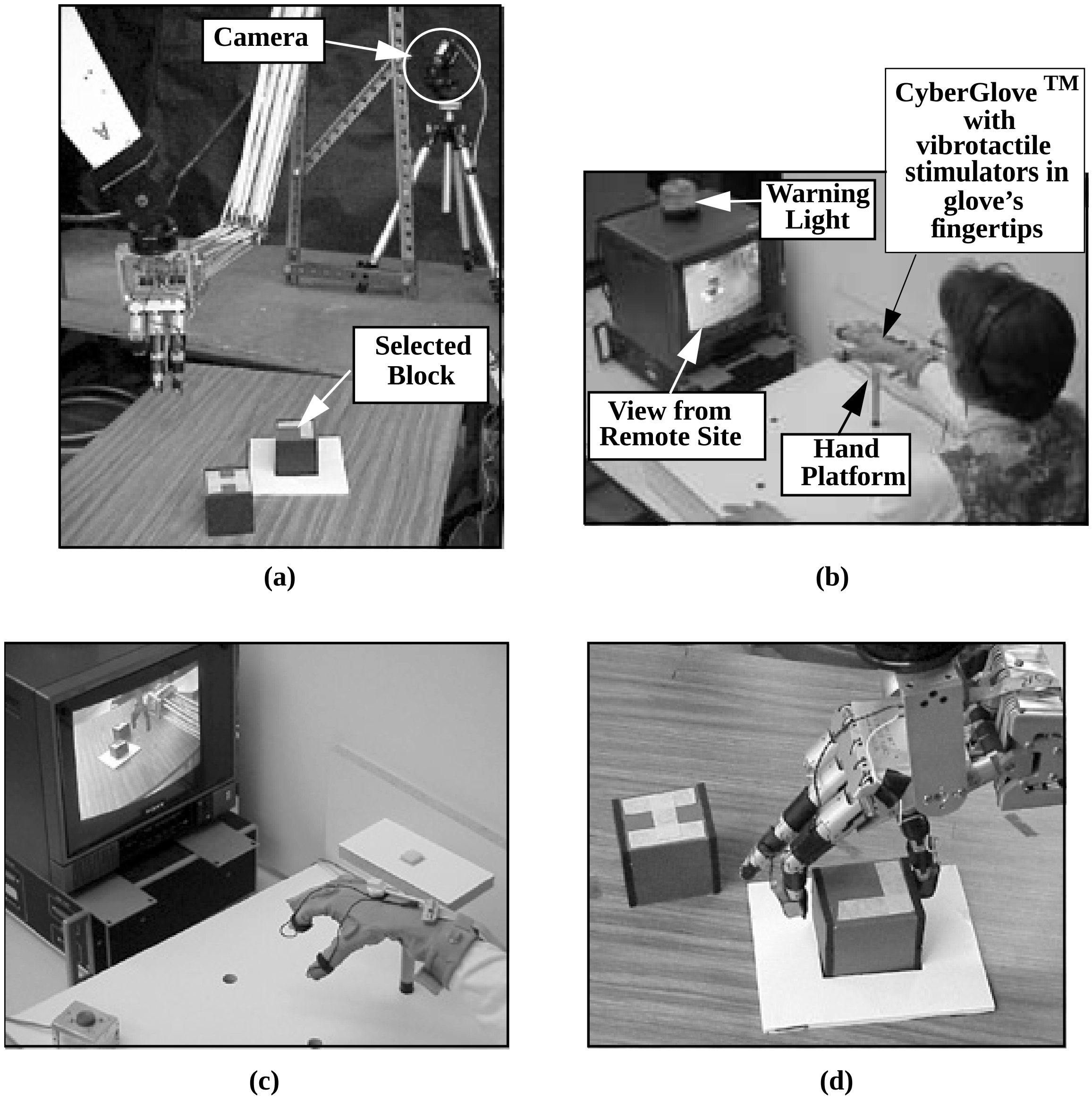


Figure 7. The mean magnitude estimates with standard error bars for the finger groups at each of the six stimulus levels, relative to signal amplitude (1 volt referenced to approximately 14 µm loaded displacement) (see Table 1 for signal frequency). After Murray, Klatzky, & Khosla (1999).



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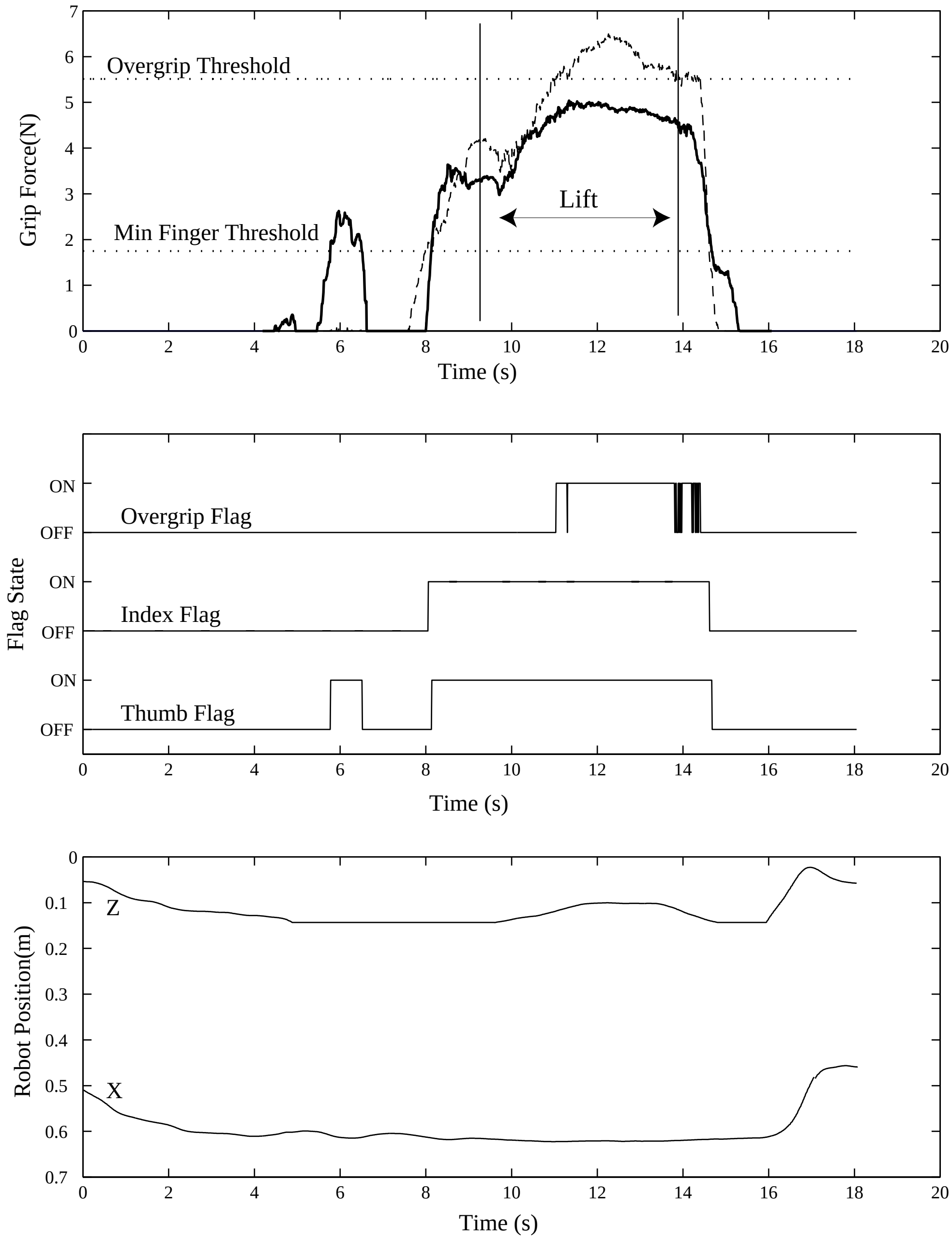

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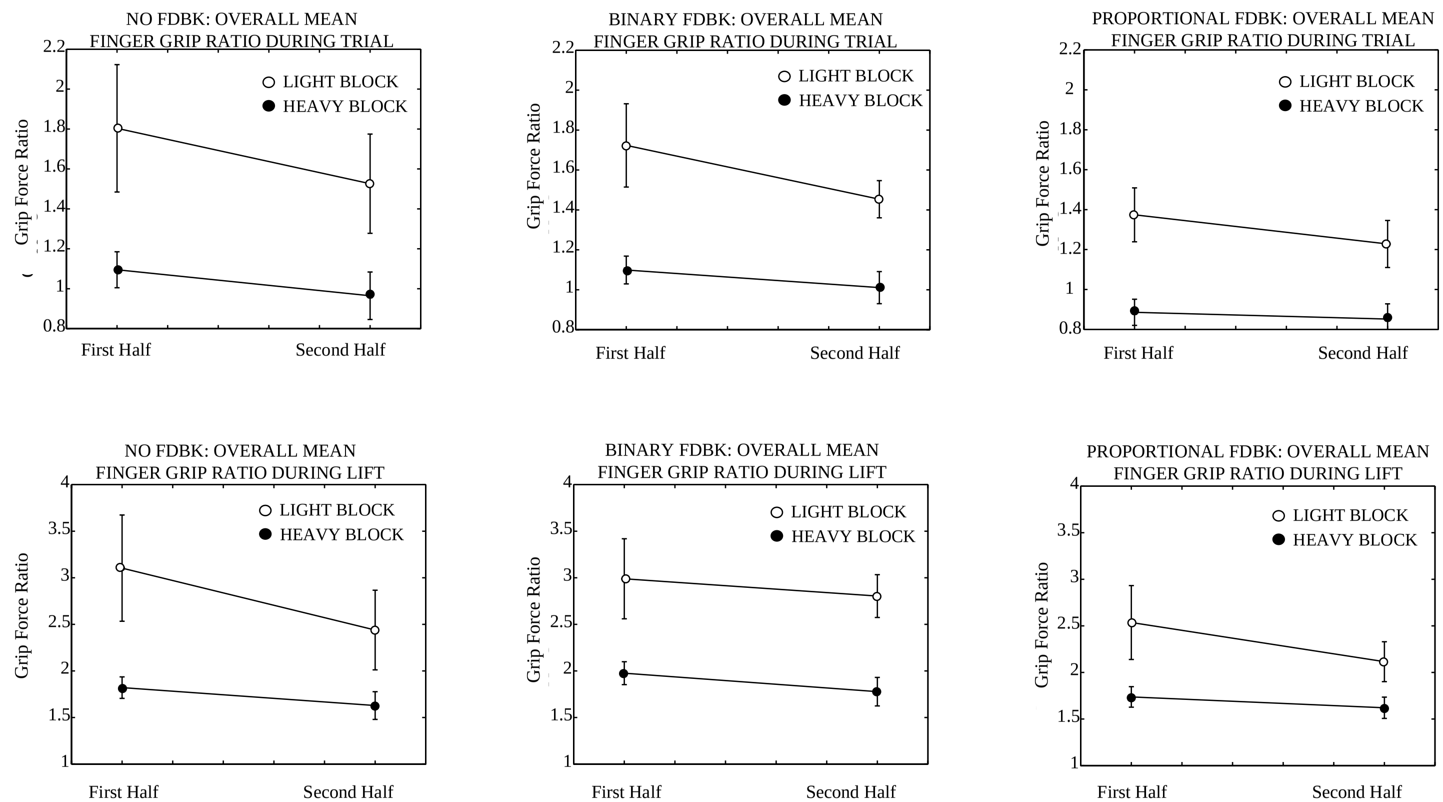

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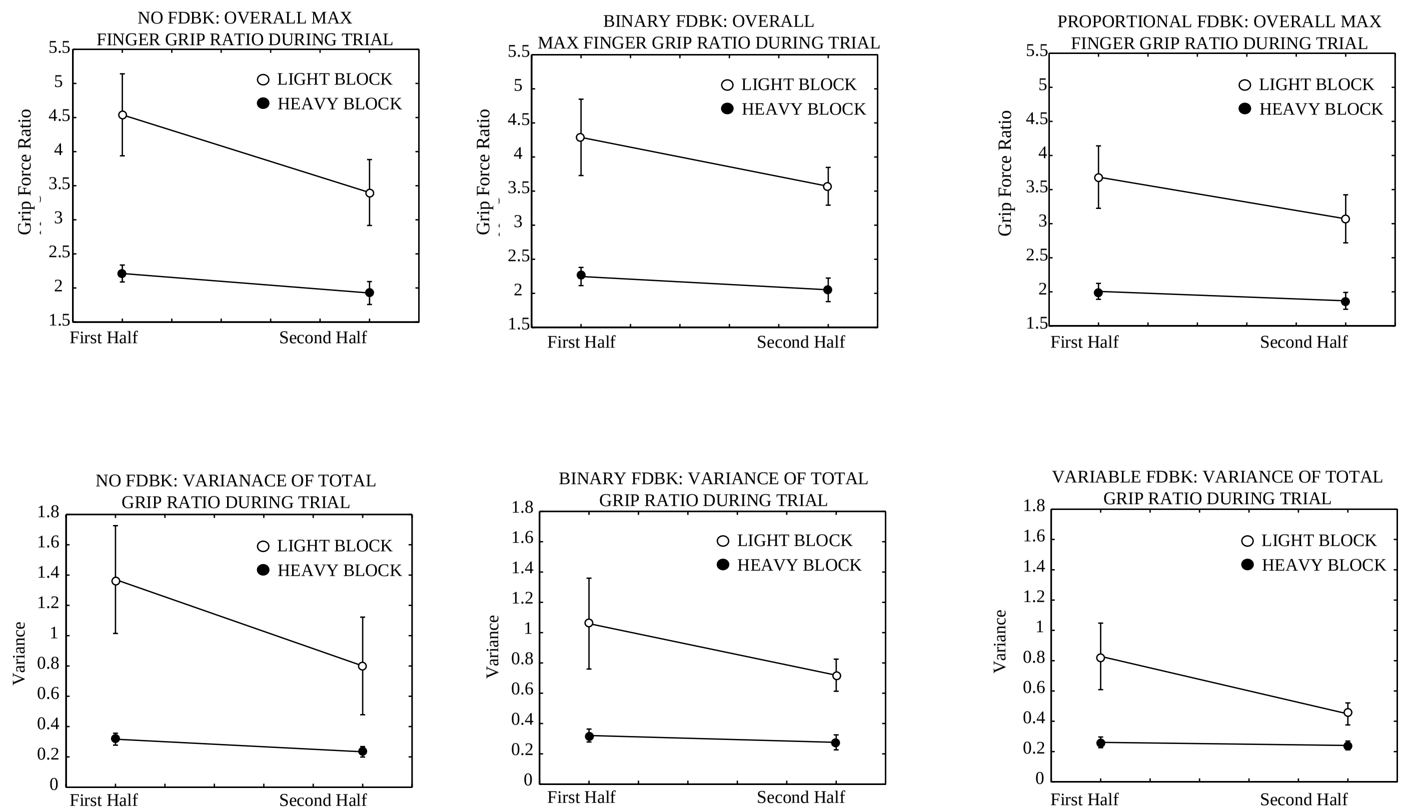

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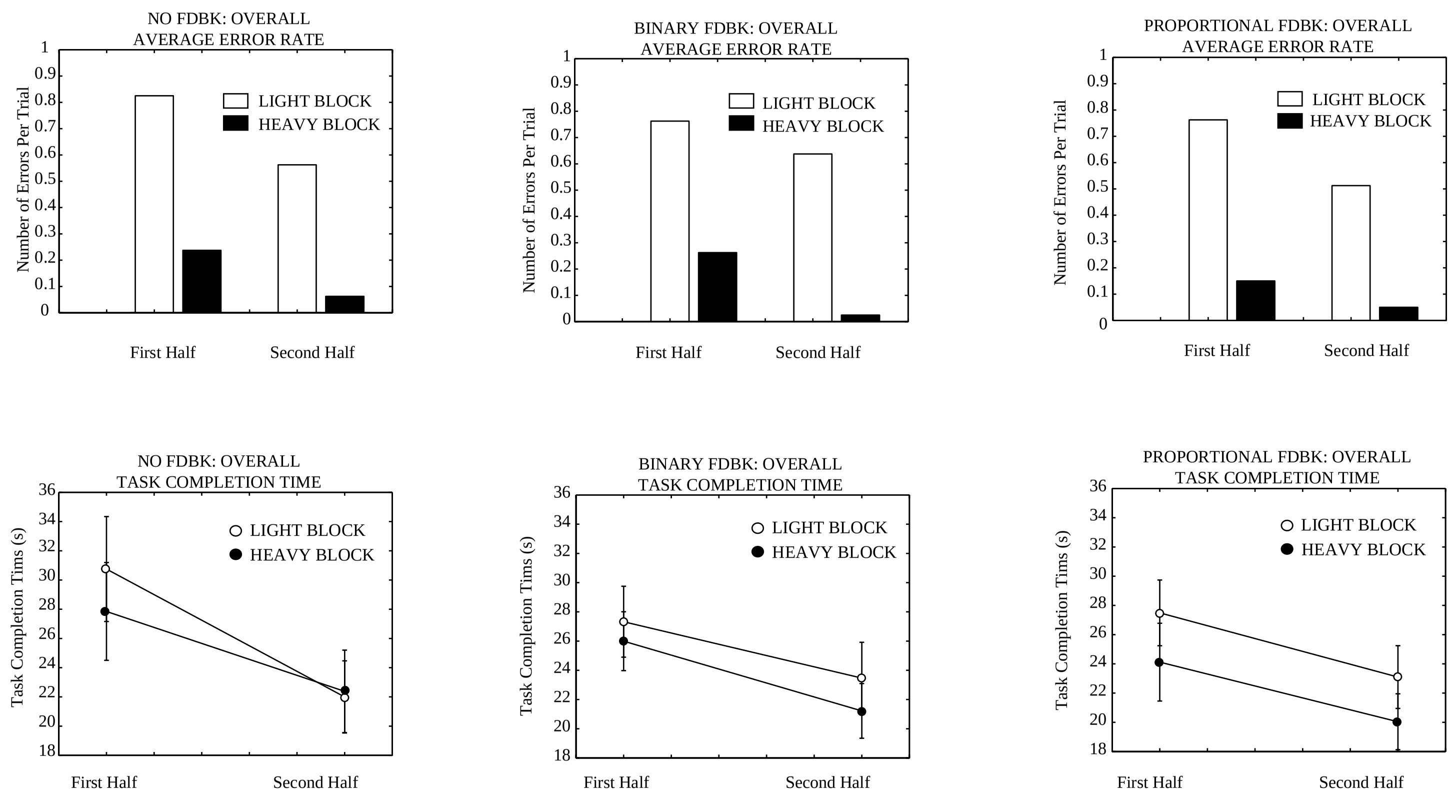

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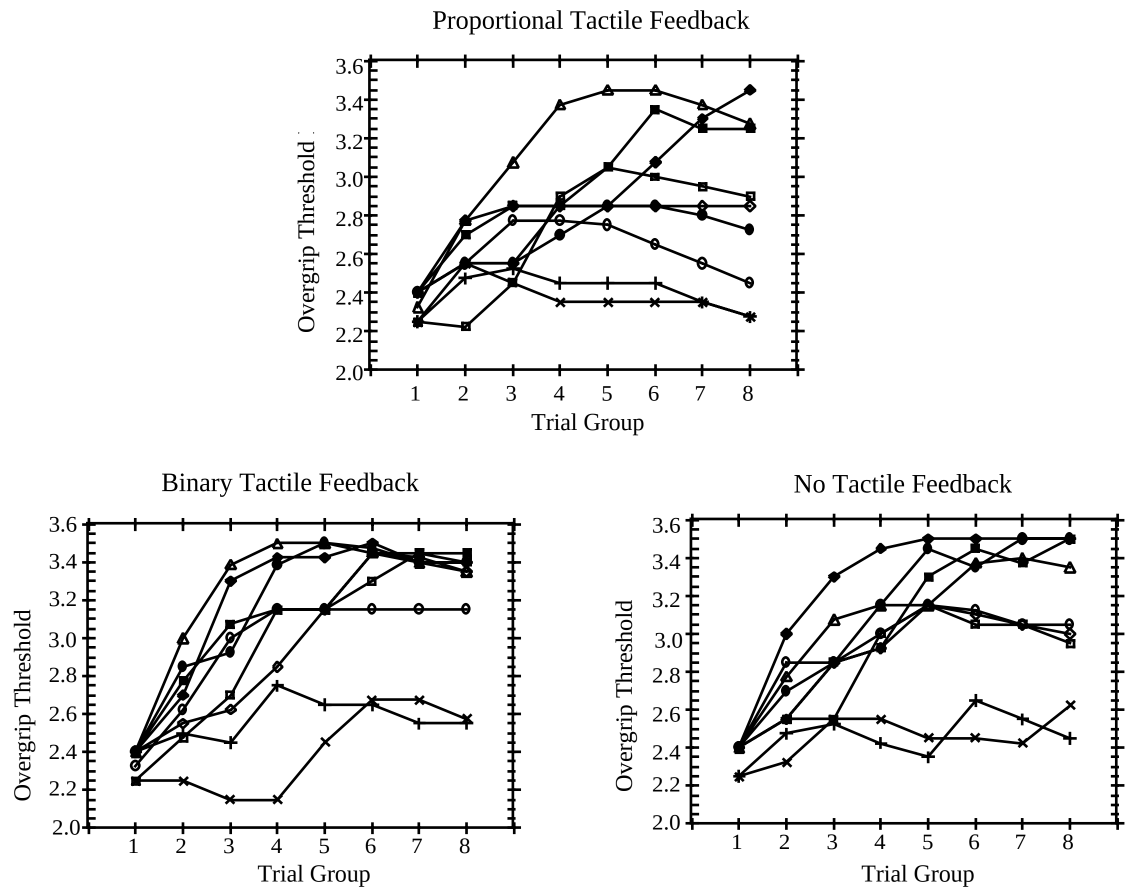

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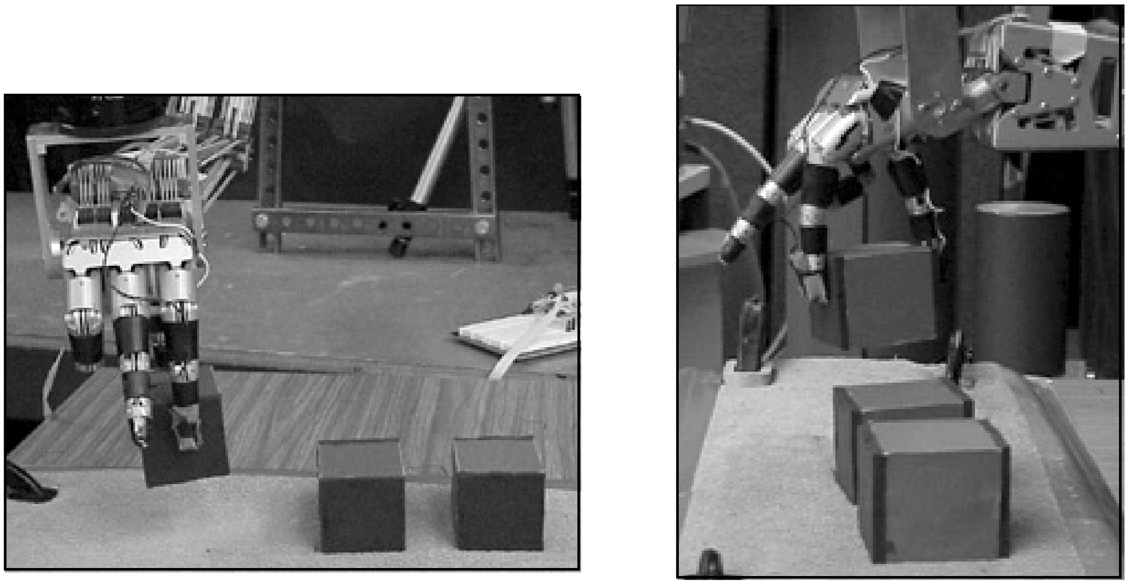

(a) **(b)**

Figure 14. An overview of the sorting experiment: (a) shows a front angle view as the robot hand is teleoperated to pick up one of the three blocks; (b) shows a side view of the task.