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HUMAN PERFORMANCE IN CONTROLLING NORMAL FORCES OF CONTACT WITH RIGID OBJECTS

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INTRODUCTION

In any manual task involving physical contact with an object, be it for exploration or manipulation, sensing and control of contact conditions are equally important for successful performance. In humans, rich sensory information is provided by a wide variety of sensors that monitor the tasks continuously, and the control action can range from a fast reflex to a relatively slow conscious deliberate action. The human abilities of tactual perception and manipulation are dependent on the proper functioning of the haptic system consisting of the mechanical, sensory, motor, and cognitive subsystems.

Tactual sensory information concerning contact with an object can be divided into two classes: (i) Tactile information, referring to the sense of the type of contact with the object as well as some of the physical properties of the object, mediated by the responses of receptors innervating the skin within and around the contact region; (ii) Kinesthetic information, referring to the sense of position and motion of body segments along with the associated forces, conveyed not only by the sensory receptors in the skin around the joints, joint capsules, tendons, and muscles, but also by neural signals derived from motor commands. In addition to the tactile and kinesthetic sensory channels, the human haptic system also includes the motor subsystem which enables control of body postures and motions together with the forces of contact with objects.

Haptic interfaces are devices that enable manual interactions with virtual environments or teleoperated remote systems. Such interactions may or may not be accompanied by the stimulation of other sensory modalities such as vision and audition. In performing tasks with a haptic interface, the human user conveys desired motor actions by physically manipulating the interface, which, in turn, displays tactual sensory information to the user by appropriately stimulating his or her tactile and kinesthetic sensory subsystems. Thus, in general, haptic interfaces can be viewed as having two basic functions: (1) to measure the positions and contact forces (and time derivatives) of the user's hand (and/or other body parts) and (2) to display contact forces and positions (and/or their spatial and temporal distributions) to the user. Among these position (or, kinematic) and contact force variables, the choice of which ones are the motor action variables (i.e., inputs to the computer or the slave robot) and which are the sensory display variables (i.e., inputs to the human) depends on the interface design, as well as the tasks for which the interface is used. Basic understanding of the biomechanical, sensorimotor, and cognitive abilities of the human haptic system is critical for proper design specifications of the hardware and software of haptic interfaces.

In performing manual tasks in real or virtual environments, contact force is perhaps the most important variable that affects both tactual sensory information and motor performance. When the hand is actively pressed against an object, the contact forces are sensed by both the tactile and kinesthetic sensory systems. The Just Noticeable Difference (JND) in contact force is about 7% over a wide range of conditions involving variations in force magnitude, muscle system and experimental method, provided that the kinesthetic sense is involved in the discrimination task (Pang *et al.* , 1991; Tan *et al.* , 1992). In closely related experiments consisting of distinguishing among different weights of objects, a slightly higher JND of about 10% has been observed (see reviews by Clark and Horch (1986) and Jones (1989)). An interesting illusion first observed by Weber is that cold objects feel heavier than warm ones of equal weight (see review by Sherrick and Cholewiak, (1986)). In experiments involving grasping and lifting of objects using a two-finger pinch grasp, Johansson and Westling (1984) have shown that subjects have exquisite control over maintaining the proper ratio between grasping and lifting forces (i.e., the orientation of the contact force vector), so that the objects do not slip.

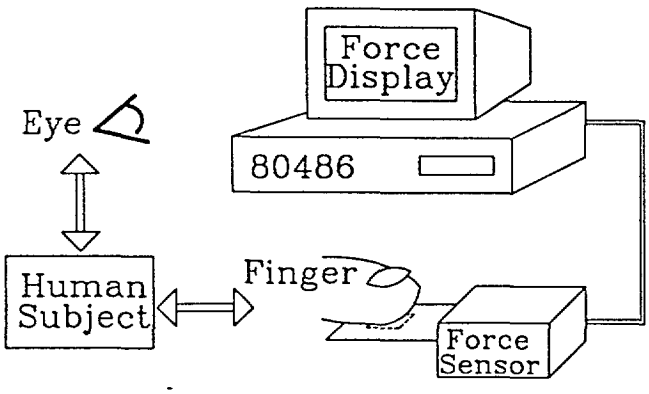

FIGURE 1: Block diagram of the experimental setup.

However, when tactile information was blocked using local anesthesia, this ability deteriorated significantly because the subjects could not sense contact conditions such as the occurrence of slip, and hence did not apply appropriate compensating grasp forces. Thus, performance in tasks involving contact require sensing of appropriate forces as well as using them to control contact conditions.

Our goals in this study were (1) To measure the human ability in controlling normal force of contact applied by the fingerpad under several experimental conditions and (2) to determine the relative importance of various sources of sensory feedback in aiding control performance. The experiments consisted of tracking several time-profiles of forces displayed on a computer monitor by human subjects whose fingerpads were in contact with a force sensor. In order to isolate the effect of various sensory feedback sources, the same experiments were performed with normal and locally anesthetized fingertips, and in a few cases without visual feedback as well. The absolute error between the target and the subjects' response averaged over several trials by each subject and over subjects served as a measure of human performance.

METHODS

Figure 1 shows the block diagram of the experimental setup consisting of a custom made six-axis force sensor interfaced to an analog to digital (A/D) conversion board on a 80486 personal computer. Three human subjects with normal visual and tactile abilities participated in the experiments.

Each subject was seated so as to comfortably press his/her index fingerpad on a glass plate attached to the force sensor. At the beginning of each trial a target force time profile was displayed on the computer monitor. The subject was instructed to exert normal force on the glass plate to track the displayed target force as closely as possible. The computer program for data acquisition was set up such that the subjects had to exert a force exceeding 0.1N in order to start a trial. In most cases, the actual force applied by the subject was also displayed on the computer monitor to serve as visual feedback. In the experiments, the distance between the eyes of the subjects and the computer monitor was about 50 cm. The force sensor used had a range of 5N and the effective resolution achieved with a 12 bit A/D board was better than 0.01N after allowing for errors due to quantization and noise. The sampling rates used for data acquisition ranged from 100 to 300 samples/sec. depending on the duration of the tasks. In each trial, 4000 data points were acquired, of which every eighth point was displayed in order to show the entire trace on the monitor.

Three target profiles were used in the experiments: constant, linear ramps and sinusoids. The vertical axis on the monitor represented the force value and the horizontal axis represented time. The complete target profile appeared on the screen before the start of each trial and remained until a specified time. The constant force target was displayed as a horizontal line at a height of 3.6 inches (equivalently, 300 pixels) above the origin. The ramp target was displayed as an inclined line that started at the origin on the left side of the screen and increased linearly until a point 3.6 inches (300 pixels) above the origin was reached on the right side of the screen. Two full periods of the sinusoidal targets were displayed, covering the full width of the screen with a height of 3.6 inches (300 pixels) peak-to-peak.

The same target profiles described above represented different force values and durations in different trials. The constant force ranged from 0.25N to 1.5N in 0.25N steps, and each trial lasted for 14 seconds. The ramp target was always from 0N to 1.5N, but the durations varied among 14, 21 and 37 seconds. The amplitudes of the forces in sinusoidal targets varied among 0.5, 1.0 and 1.5N, whereas the durations were 14, 21 and 37 seconds for each amplitude. Trials with each set of parameters were repeated three times, and all the trials were randomly presented, with the sequence of stimuli being the same for all the subjects. Before the beginning of the experiments, practice trials including different targets and different force ranges were given.

In order to determine the importance of tactile feedback in controlling the contact force on the fingerpad, the tracking experiments were conducted with the subject's finger under normal conditions (both tactile and kinesthetic information available to the subject) as well as with local cutaneous anesthesia administered to the middle phalanx which blocked tactile information from the fingerpad (only kinesthetic information available to the subject). The data was collected from the same three subjects under both conditions. Experiments under normal conditions were conducted first, and after at least two days the experiments under anesthetized

conditions were performed. Only in the case of the constant force target were trials conducted without visual feedback. The experimenter verbally called out to the subject when he/she first reached the target force value, after which the subject was to try and maintain the force at that value until the end of the trial.

Several measures of the tracking error between the target profile and the subjects' performance were computed: (1) the standard deviation calculated after subtracting the variance of the force sensor noise from the variance of the tracking error; (2) the absolute error; (3) the absolute error expressed as a percentage of the target force at each instant of time. The results described below are given in terms of the absolute error averaged across trials and subjects. Because the threshold force for the start of each trial was set at 0.1N, some artifacts were introduced in the data near the beginning of each trial. Therefore only the data for target forces greater than 0.2N were analyzed.

RESULTS

Constant Force

Typical data concerning the force exerted by the subjects in tracking the constant force target was as shown in Figure 2. Any force variations at frequencies greater than about 20 Hz are due to noise in the force signal since the power spectral density plots showed that the subjects' performance was indistinguishable from the noise in the unloaded force signal for high frequencies. As was mentioned before (see METHODS) the amplitude of the noise was less than 0.01N.

Visual inspection of the raw data and mean absolute error for each trials and subject showed no distinguishable differences in the performance of the subjects. The absolute error averaged across all trials and subjects for each of the constant force levels and experimental condition is shown in Figure 3. In the case of normal finger without visual feedback, the average absolute error increased with the target force magnitude and was generally between 11 to 15%. When visual feedback was present, the error not only reduced significantly, but also remained approximately constant at 0.039N $\pm$ 0.006 SD for all the target force values. When the fingers were anesthetized, the error in both the presence and absence of visual feedback followed the same trend as the corresponding normal finger cases, but was higher by about 0.02 to 0.05N. Thus, whereas the presence or absence of visual feedback changed both the magnitude of the error and its variation with respect to target force value, the presence or absence of tactile feedback only changed the error magnitude.

Ramp Force

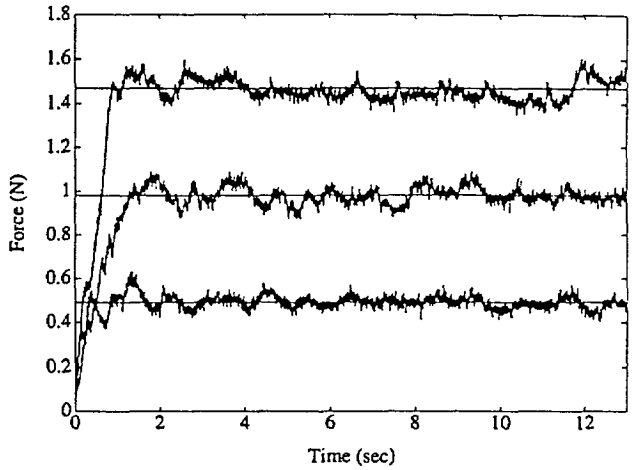

FIGURE 2: Data collected from individual trials of a subject's tracking of constant forces under normal conditions with visual feedback. The target forces were 0.5, 1.0 and 1.5N.

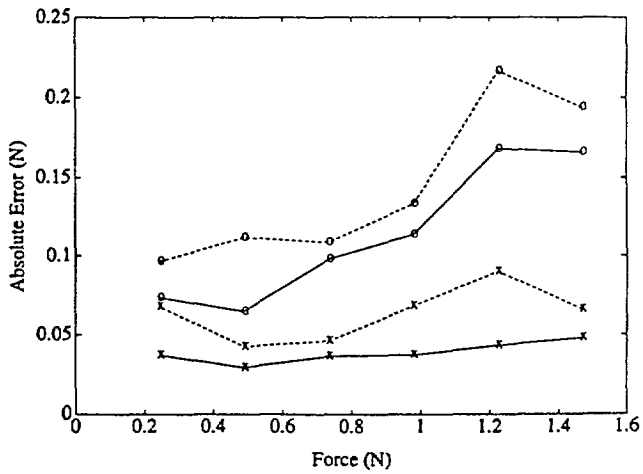

FIGURE 3: The mean absolute error averaged across all trials and subjects for each force and experimental condition in tracking of constant forces. Solid and dashed lines represent normal and anesthetized conditions respectively. Data points marked with symbol 'x' indicate the presence of visual feedback, whereas symbol 'o' indicates the absence of visual feedback.

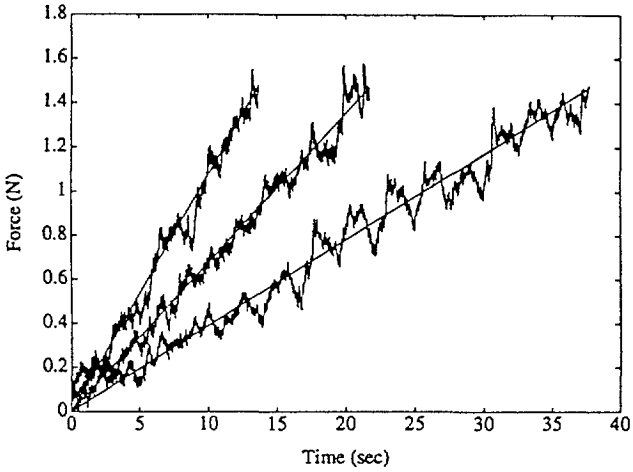

FIGURE 4: Data collected from individual trials of a subject's tracking of ramps under normal conditions with visual feedback. Three typical ramp at fast, medium, and slow force rates are shown. The force rates were 0.040, 0.069 and 0.110 N/sec.

Three linear ramp targets used in the experiments had effective force rates of 0.04N/sec, 0.069N/sec and 0.110N/sec. The target displayed for these ramps looked the same on the monitor, with the only difference being the duration of the trials. Figure 4 shows typical responses of a subject to ramps at fast, medium and slow force rates.

The absolute error averaged across all trials and subjects for each force rate under normal conditions is shown in Figure 5. For target forces greater than 0.2N, the absolute error is generally independent of both the target force, magnitude and rate. The error calculated from each of the three traces in Figure 5 are 0.054N ± 0.018 SD for the slow rate ramp, 0.048N ± 0.015 SD for the medium rate ramp and 0.054N ± 0.015 SD for the fast rate ramp. Thus, there are no distinguishable differences in the performance of the subjects at the three force rates.

Figure 6 shows the results of medium rate ramp force experiment under both normal and anesthetized conditions. The absolute error in the anesthetized condition was 0.073N ± 0.024 SD as compared to 0.048N ± 0.015 SD for the normal condition. The results for the anesthetized condition at the other two force rates are about the same as the anesthetized condition for the medium force rate and are summarized in Table 1.

From the results, the following observations were made. First, the force rates used in the ramp target had no effect on the subjects' performance in both normal and anesthetized conditions. Second, the mean error in the anesthetized conditions was about 0.02N higher than that in the normal con-

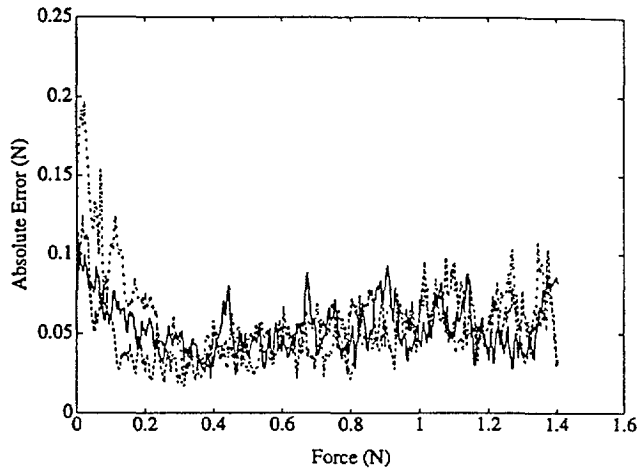

FIGURE 5: The mean absolute error averaged across subjects and trials in tracking of ramp forces for each force rate under normal conditions. Solid, dashdot and dashed lines represent fast, medium and slow force rates respectively.

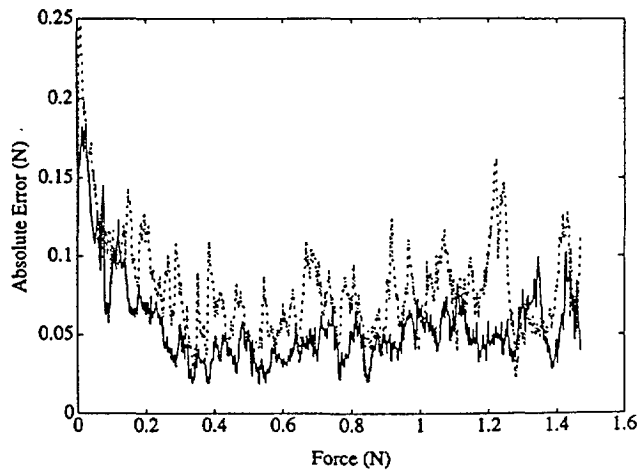

FIGURE 6: The mean absolute error during tracking of a ramp force at medium force rate under normal (solid line) and anesthetized (dashdot line) conditions.

Target Profile	Average Force Rate (N/sec)	Absolute Error (N)			
		Normal Condition		Anesthetized Condition	
		MEAN	SD	MEAN	SD
Constant - all forces with vision	0 000	0 039	0.006	0.063	0.017
Ramp					
slow	0.040	0.054	0.018	0.067	0.019
medium	0.069	0.048	0.015	0.073	0.024
fast	0.110	0.054	0.015	0.074	0.025
Sine 0.5N					
slow	0.054	0.043	0.009	0.057	0.012
medium	0.095	0.044	0.010	0.066	0.011
fast	0.152	0.046	0.007	0.068	0.014
Sine 1.0N					
slow	0.107	0.061	0.011	0.084	0.022
medium	0.190	0.065	0.009	0.080	0.011
fast	0.302	0.092	0.012	0.091	0.010
Sine 1.5N					
slow	0.159	0.076	0.019	0.137	0.022
medium	0.277	0.106	0.023	0.135	0.031
fast	0.441	0.135	0.023	0.194	0.040

TABLE 1: Mean and standard deviations obtained from the absolute error vs. force traces averaged across trials and subjects for each experimental conditions.

dition. Third, the mean error in tracking ramp targets was slightly (0.1N) higher than that in tracking constant force targets.

Sinusoidal Force

Typical data collected from a subject's tracking of sinusoidal forces of three different amplitudes for medium duration (21 seconds) is shown in Figure 7. The amplitudes were 0.5, 1.0 and 1.5N. As in the case of the ramp forces, the target display was the same for all ranges and durations.

In order to compare with the results for ramp forces, only the results from the increasing portion of the sinusoids are reported here. Shown in Figure 8 are absolute errors averaged across all subjects and trials for three different durations of the 1.0N amplitude sinusoid tracked with normal fingers. The average force rate in the long duration trials was 0.107 N/sec, whereas those for the medium and short durations were 0.190 and 0.302 N/sec, respectively. The absolute error was 0.061N $\pm$ 0.011 SD for the slow force rate sinusoid, 0.065N $\pm$ 0.009 SD for the medium sinusoid, and 0.092N $\pm$ 0.012 SD for the fast sinusoid.

Figure 9 shows mean absolute error for the medium duration 1.0N amplitude sinusoid tracked under normal and anesthetized conditions. The absolute error remained generally independent of the target force magnitude in both cases. The mean error for the anesthetized condition was 0.080N $\pm$ 0.011 SD, which was slightly higher than that for the normal condition (0.065N $\pm$ 0.009 SD). Results for other parameter combinations are listed in Table 1.

From the results, the following observations were made. First, the variation in average force rates did affect the sub-

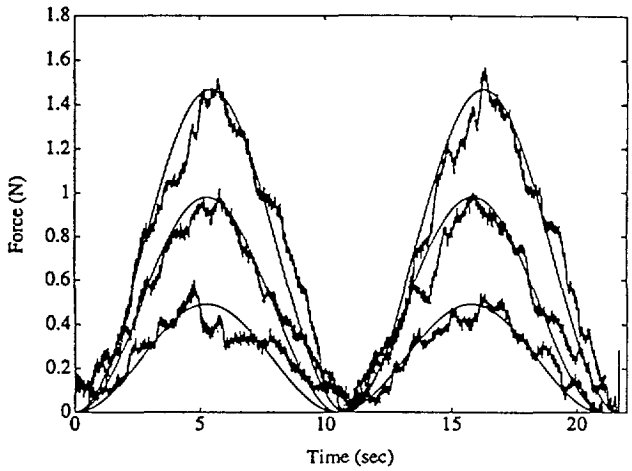

FIGURE 7: Typical data collected from individual trials of a subject during tracking of sinusoids under normal conditions with visual feedback. Data for 0.5, 1.0 and 1.5N amplitude sinusoids are shown.

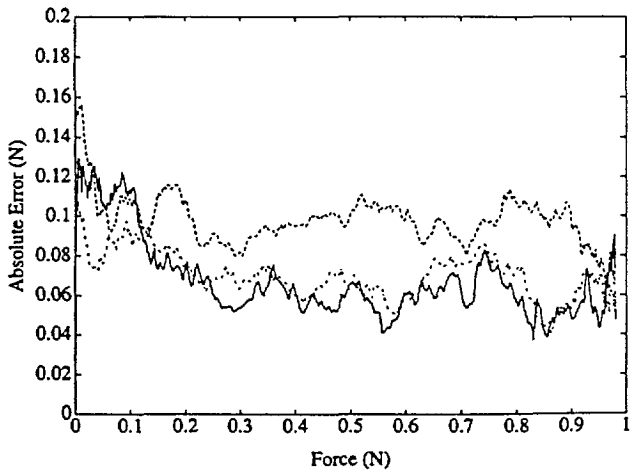

FIGURE 8: The mean absolute error for 1.0N amplitude sinusoidal targets with three different durations and tracked under normal conditions. The data for the increasing phase of the sinusoids are shown. Solid, dash-dot and dashed lines represent slow, medium and fast sinusoids respectively.

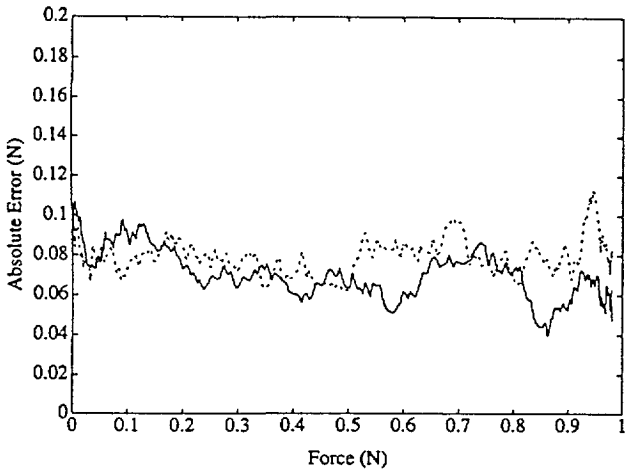

FIGURE 9: The mean absolute error in tracking the medium duration 1.0N amplitude sinusoid under normal (solid line) and anesthetized (dashdot line) conditions.

jects' performance in tracking sinusoidal forces. For example, the mean absolute error for the short duration 0.5N sinusoid was 0.046N. In comparision, the error for the 1.0N and 1.5N sinusoids were 0.092N and 0.135N. Second, the mean errors from the anesthetized conditions were consistently larger than those for the normal conditions. Third, the tracking performance for the long duration 1.0N sinusoid was slightly worse than that for the fast ramp, although the average force rates were approximately the same (Table 1).

DISCUSSION AND CONCLUSIONS

Among all the experimental conditions described in this paper, tracking constant forces with normal finger when visual feedback was absent is the one closest to the experiments reported in the literature on force perception JND (see INTRODUCTION). In this case, the tracking error increased with target force magnitude, as was the case with JND for force. But the error measured in the current experiments was generally between 11 to 15% as compared with the force JND of 6-8% mentioned in the literature (Pang *et al.*, 1991; Tan *et al.*, 1992). This difference could be due to (1) what is measured here is the human ability in controlling the contact force, and not just sensing it, (2) the increased difficulty of the present experimental task where the subjects had to rely on the memory of the force they were exerting at the time the experimenter called out that they had reached the target force. Further experiments are being planned to minimize the effect of the latter.

One surprising result which is common to all the tracking experiments with visual feedback (with or without local anesthesia) is that for each experimental condition, the absolute tracking error does not vary (in a statistical sense) with target force magnitude. This is not due to any artifact introduced by the visual acuity of the subjects in resolving the difference between the target force trace and the subject's response trace: (1) even 1 pixel difference between the two traces is higher than visual resolution and was clearly noticeable; (2) in experiments on tracking constant force, since the visual display was the same for all the forces, if error expressed as number of pixels had remained the same for all the forces, the absolute error in Figure 3 should have linearly increased with force; (3) in experiments on tracking ramp force, the error in terms of pixels was higher than that for constant forces; (4) in experiments on tracking sinusoidal forces, since the visual display was the same for amplitudes of 0.5, 1.0 and 1.5N, the magnitude of the absolute error in force units should have been proportional to the amplitudes (similar arguments as in (2) above). Therefore, the error observed is a measure of the performance of the full sensorimotor system of the subjects.

Table 1 shows the means and standard deviations obtained from the absolute error vs. force traces averaged across trials and subjects for each experimental condition. We shall now discuss the effect of various parameters and conditions on the absolute error in tracking.

Effect of tactile feedback

Comparison of the subjects' ability in tracking a particular target with normal and locally anesthetized fingertips gives the role of tactile feedback on control of contact force. In all cases, lack of tactile feedback increased the mean absolute error by 0.01 to 0.06N (Table 1; Figures 6 and 9), which meant an increase of 25 to 80%. But the general trend of the error being independent of the target force remained, with more scatter in the data as indicated by the higher standard deviations in more than half the cases. This is yet another indication that the performance measured is not purely due to visual feedback.

Effect of force rate

The force rate was varied for both the ramp and sinusoidal target forces. The data in Table 1 (and Figures 5 and 8) shows that force rate changes did not significantly affect tracking performance for ramp forces and 0.5N amplitude sinusoids. In other cases, higher force rate generally increased the mean error.

Effect of target profile

The effect of the target profile wave on the absolute error in experiments with normal finger can be seen in Figure 10.

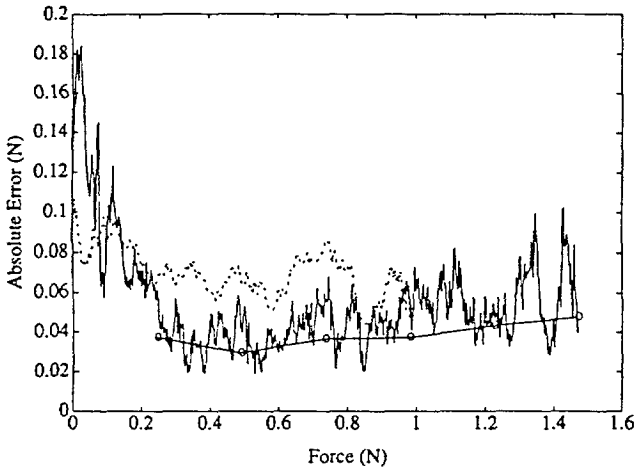

FIGURE 10: The mean absolute error in tracking the three different target profiles under normal conditions and with visual feedback. The data for constant force target is represented by o-o line. The force rates for the ramp (solid line) and sinusoidal (dashdot line) targets are approximatedly equal (0.110N/sec and 0.107N/sec respectively).

The constant force target had the least error. Although the average force rate was about the same for the ramp and sinusoidal force cases shown, the mean error was higher for the sinusoid. As seen from Table 1, the mean error for both normal and locally anesthetized fingertips increased in the order of constant force, 0.5N sinusoid, ramp, 1.0N sinusoid and 1.5N sinusoid. It should be noted that that 0.5N sinusoid had lower errors even when the average force rates were higher than those for the ramps. This result together with the opposite effect for the ramp and sinusoid cases shown in Figure 10 indicate that the interaction effects between force rate and target profile are not simple.

From a systems viewpoint, an issue that arises is the nature of the underlying dynamic system that gives rise to the observed human control performance, such as the oscillatory response for a constant input signal (Figure 2). It is well known that time delays are present due to transmission of neural signals in visual and tactual sensory pathways, cognitive processing and actuation of the motor system. The results given here can be thought of as generated from a linear system with inherent time delays and a loop gain that varies in the neighborhood of unity. The range of this variation determines the variability of the amplitude of the tracking error. Alternatively, a combination of nonlinearities such as deadzone, hysterisis and saturation in the sensorimotor system can induce a limit cycle behavior (Ogata, 1990) similar to those observed in the data obtained here on human force control.

The abilities of the human haptic system set the design specifications of haptic interfaces. It is possible that the human errors measured here under normal conditions with visual feedback represent a lower bound on the human haptic performance in controlling normal forces of contact with rigid objects. As is to be expected, the errors were higher under anesthetized conditions or with the absence of visual feedback. A design specification that arises from the results given here is that haptic interfaces need to have a force resolution of at least 0.01N in order to make full use of human haptic capabilities.

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