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HUMAN FACTORS FOR THE DESIGN OF FORCE-REFLECTING HAPTIC INTERFACES

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ABSTRACT

This paper discusses the design criteria imposed by the capabilities of the human user on the design of force reflecting controllers for hands and arms. A framework of issues regarding human capabilities is presented that maps directly to mechanical design requirements. The state of knowledge for each capability is briefly summarized along with presentation of new experimental measurements. Finally, the implications of the human factors data to haptic interface design are discussed.

1. INTRODUCTION

Haptic interfaces are devices that enable manual interactions with virtual environments or teleoperated remote systems. Although haptic interfaces are typically designed to be operated by the user's hands, alternative designs suitable for the somatosensory and motor systems of other body segments are conceivable. However, not all interfaces that interact with the human mechano-sensorimotor systems are haptic interfaces. The distinction is based on the nature of the tasks for which the interface is used. For example, "whole body movement displays" (Durlach, Pew, Aviles, DiZio, & Zeltzer, *Eds*., 1992), concerned with conveying a sense of mobility to the user, are not haptic interfaces in a strict sense.

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. In this paper, we focus on interfaces that are capable of displaying net contact forces, and not their spatial distributions. Even with this simplification, large improvements on existing devices can only be achieved by a proper match between the performance of the device and human haptic abilities.

Due to inherent hardware limitations, haptic interfaces can only deliver stimuli that approximate our interactions with the real environment. It does not, however, follow that synthesized haptic experiences created through the haptic interfaces necessarily feel unreal to the user. Consider an analogy with the synthesized visual experiences obtained while watching television or playing a video game. While visual stimuli in the real world are continuous in space and time, these visual interfaces project images at the rate of about 30 *frames/sec*. Yet, we experience a sense of realism and even a sense of telepresence because these displays are able to exploit the limitations of the human visual apparatus.

The hope that the necessary approximations in generating synthesized haptic experiences will be adequate for a particular task is based on the fact that the human haptic system has limitations that can be exploited. To determine the nature of these approximations, or, in other words, to find out what we can get away with in creating synthetic haptic experiences, quantitative human studies are essential. Basic understanding of the biomechanical, sensorimotor, and cognitive abilities of the human haptic system is critical for proper design specification of the hardware and software of haptic interfaces.

In this paper, we are mainly concerned with quantitative measures of human factors that affect the design specifications of force-reflecting haptic interfaces. It should be noted that the results are applicable to both ground-based controllers and body-based exoskeletal devices. In section 2, we summarize a general framework that specifies the major capabilities of the human hand and arm that are directly related to interface design. Relevant data from published literature are reviewed. In section 3, we present the relevant data from the experiments we conducted on human subjects. Some of these results have been summarized in Chang, Tan, Eberman, & Marcus (1993). In section 4, we discuss the implications of the human factors data to device design.

2. FRAMEWORK

Compared to vision and audition, our understanding of human haptics, which includes the sensory and motor systems of the hand, is very limited. One of the reasons is the experimental difficulty of presenting controlled stimuli, owing to the fact that the haptic system is bidirectional - it can simultaneously perceive and act upon the environment. In our haptic interface design experience, the major perceptual issues are: 1) force sensing under quasi-static and dynamic conditions, 2) pressure perception, 3) position sensing resolution, and 4) the level of stiffness required for rigidity simulation. The major manual performance issues are: 1) the maximum forces humans can produce, 2) the precision with which humans can control a force, and 3) the control bandwidth of force. The issues of ergonomics and comfort are also important, but are beyond the scope of this paper.

A. Force Sensing

(i) Slowly-Varying Forces. In order for the human user to perceive the forces displayed by the device as smoothly varying, the force display resolution of the device should match or exceed human sensing resolution. We found from literature that the Just-Noticeable-Difference (JND) for human force sensing is around 7% (Jones, 1989; Pang, Tan, & Durlach, 1991) regardless of test conditions (Jones used contralateral isometric force-matching procedure; Pang *et al.* used one-interval two-alternative forced-choice discrimination paradigm), body sites (Jones studied forced generated by the elbow flexor muscles; Pang *et al.* studied force generated by actively squeezing the thumb towards the index finger), reference forces (Jones: 25 to 410 *Newtons*; Pang *et al.*: 2.5 to 10 *Newtons*) and other parameters.

(ii) Vibration. One of the most noticeable disturbances in a force reflecting device is the level of unintended vibration. A significant level of vibration can quickly destroy the feeling of free motion or disturb the perception and control of virtual objects in contact. According to the literature (e.g., Bolanowski Jr., Gescheider, Verrillo, & Checkosky, 1988), the detection threshold for vibrotactile stimulation is roughly 28 dB (re 1 *micron*) below 30 Hz and decreases at a rate of roughly -12 dB/oct from 30 to 300 Hz. After that, the threshold rises again. This is a very tight constraint on the device, and requires careful attention to all the aspects of hardware design and control software.

B. Pressure Perception

Many force-reflecting exoskeletons are being designed that are attached to the user's forearm in order to display contact forces at the fingerpads. This implies that an unbalanced contact force at the fingerpad, which would have been supported by the entire upper body in the real world, is now equilibrated (or, mechanically grounded) at the forearm, and the rest of the user's body does not experience the effects of this force. The perceptual effectiveness of such a non-realistic display is unknown. The grounding location on the user's body and the contact geometry have to be judiciously chosen such that they create an illusion of a true earth ground. The true ground illusion might be successfully produced if the pressure distribution and its changes at the grounding location are below the absolute detection and discrimination thresholds, respectively, for the human user. The results of our study on pressure discrimination threshold as a function of contact area are presented in Section 3.1.

C. Position Sensing Resolution

The position sensing resolution that is desired of the device depends, among other factors, upon the position resolution of the human operator. Only human joint angle resolutions that are directly related to the fingertip position are discussed here. In a separate study, we have found that the JND of the Proximal-InterPhalangeal (PIP) and the MetaCarpal-Phalangeal (MCP) joint to be about 2.5° (RLE Progress Report, 1992). New experiments and data on the wrist, elbow, and shoulder joints are described in Section 3.2 using the same experimental paradigm and similar test devices scaled to accommodate different joint sizes. Some subjects served in the current as well as our previous studies.

D. Stiffness

Mechanical behavior of most solid objects in a virtual world are modeled with elastic stiffness, and many are supposed to appear rigid. In the context of virtual environments, rigidity is a perceptual notion, which requires an engineering specification, i.e., what is the stiffness required to convince a user that an object is rigid? Note that perceived rigidity depends upon not only the stiffness of the interface hardware, but whether the comparison is done among a set of virtual wall simulations or between a simulation and a real wall. For example, Rosenberg and Adelstein (1993) used a set of virtual walls to study three perceptual attributes: the crispness of initial contact, the hardness of surface rigidity, and the cleanness of final release. They found that subjects could consistently judge the relative "wallness" of the simulations despite the fact that none of them felt real. Although there is a general consensus that virtual walls are never as rigid as real walls due to hardware limitations (Colgate, Grafing, & Stanley, 1993), we wanted to find out the absolute detection threshold of stiffness so as to establish a goal for hardware design. In Section 3.3, we report on a measurement of the human perceptual threshold of rigidity.

E. Human Force Control

(i) Range. To match human performance, the maximum force exerted by the device should meet or exceed the maximum force humans can produce. The literature contains very little specific information. We report on some experimental measurements of this output for different joint angles in Section 3.4.

(ii) Resolution. This is the resolution at which the force/torque on a joint linkage must be controllable. In order to present a perceptually smoothly varying force, the forces displayed by the device must be controllable to at least the level at which humans can sense and control force. Again, data for specific joint configurations is required, and we report on some new experimental measurements in Section 3.5.

(iii) Bandwidth. The force control and perceptual bandwidths of a human operator are quite different. Whereas our somatosensory system can perceive vibrotactile stimuli up to 1000 *Hz*, the upper bound of force control bandwidth is on the order of 20 to 30 *Hz* (e.g., Stiles & Randall, 1967, found that finger tremor measured from normal adults has a spectral peak around 25 *Hz*; Srinivasan & Chen, 1993, observed from power spectral density plots of human force tracking data that an upper bound on human force control bandwidth is about 20 *Hz*). The actual bandwidth is probably considerably less, and is reported to be about 7 *Hz* (Brooks, 1990). The bandwidth of the device when it is backdriven by the human operator should at least match the force control bandwidth of the operator.

F. Ergonomics And Comfort

Sizing and fatigue are also important issues, especially for exoskeletal devices, but we will not discuss them in this paper due to limited space.

3. SUMMARY OF PSYCHOPHYSICAL EXPERIMENTS

In order to establish a minimal set of measurements on human haptic performance, we have identified the need for five new psychophysical experiments: 1) pressure perception, 2) position resolution, 3) stiffness, 4) force output range, and 5) force output resolution. The results from these studies on human perception as well as manipulation capabilities are summarized here. Note that we use the JND to characterize some of the perceptual results. These JNDs correspond to differences between two test parameters that are presented (typically several hundred times) to the human subject and are discriminated correctly by roughly 70% of the subject's responses.

3.1 Pressure Perception

The purpose of this study was to measure pressure JNDs as a function of contact area. We concentrated on the forearm, the most likely attachment site for a hand-worn force-reflecting device. Volar (i.e., palmar) and dorsal sides near both the wrist and the elbow were tested.

In order to control the contact areas, three cylinders of height 1 *cm* were cut from ready-made round Plexiglas solid rods with diameters of 1.27, 2.54, and 5.08 *cm*. Sharp corners on the contact cylinders were smoothed. Subject's forearm was fully extended in front of the torso and held in the horizontal plane. Weights were applied to the test site by hanging a container over the Plexiglas cylinder placed at the test site. The elbow joint and the wrist were always supported by flat surfaces of the same height (see Fig.1). Three reference weights (2.2, 8.9 and 35.6 *Newtons*) were used with the three different cylinders, respectively, so that the average reference pressure (i.e., weight/contact area) was kept the same regardless of contact area (i.e., 1.8 $Newton/cm^2$). We stopped testing the volar side of the wrist after one subject complained that his fingers were getting numb. We also stopped testing the dorsal side of the wrist with the 35.6 *Newtons* weight because it was too heavy to be held at that site. In general, the volar side of the wrist is not a suitable place for applying pressure for prolonged period of time because the nerves and blood vessels run very close to the skin surface and through the carpal tunnel. When pressure is applied near the carpal tunnel, it compresses the nerves and vessels underneath the skin. This can reduce the blood supply to the hand and may partially block the neural signals.

Average pressure JNDs as percentages of reference pressure are listed in Table 1. Each entry was averaged from 2 to 3 subjects. The JND for each subject and each experimental condition was estimated from 100 trials. From the "Overall average JND" in Table 1, it is clear that pressure JND decreased as a function of contact area. In other words, subjects became more sensitive to pressure changes (in terms of both percentage and increment) when contact area was enlarged. Overall, it seemed that JND was independent of test sites. Pressure JND decreased by a factor of roughly 4 (from 15.6% to 3.7%) when contact area increased by a factor of 16 (from 1.3 to 20.4 cm^2).

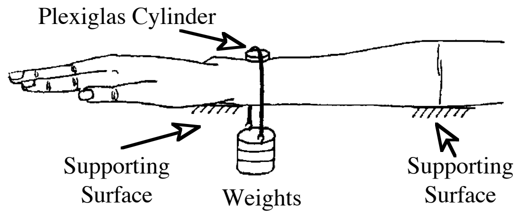

FIGURE 1.
SETUP OF PRESSURE PERCEPTION EXPERIMENTS (TEST SITE: DORSAL SIDE OF THE WRIST).

TABLE 1.
AVERAGE PRESSURE JNDs (% OF REFERENCE PRESSURE) AS A FUNCTION OF CONTACT AREA.

Body Site	Contact Area (cm^2)		
	1.27	5.06	20.27
Elbow (Volar)	16.7 %	6.2 %	4.0 %
Elbow (Dorsal)	11.3 %	5.2 %	3.3 %
Wrist (Dorsal)	18.8 %	4.4 %	
Overall Average JND	15.6 %	5.3 %	3.7 %

The average JNDs in the results above become invariant with respect to contact area if we convert them to *weight per perimeter JND*. Note that the weight JND in percentage is the same as the pressure JND in percentage for a given contact area. Therefore, the *weight per perimeter JND* in *Newton/cm* units is simply $(reference\ weight) \times (pressure\ JND\%)\ /\ (\pi \times diameter)$. This new JND was roughly 0.06-0.09 *Newton/cm* regardless of contact area. An interpretation of this result is that the subjects most probably relied on *weight per perimeter* as the main cue in discriminating pressure. This was consistent with subjects' observation that force was felt mainly around the perimeter of the contact cylinders. One explanation for the sensitivity around the contact boundary is that our tactile system is extremely sensitive to pressure gradients and especially edges (Vierck, 1977; Phillips & Johnson, 1981; Srinivasan & LaMotte, 1991).

3.2 Joint Angle Resolution

The purpose of this study was to measure the joint angle JNDs for the wrist, elbow, and shoulder joints. For the wrist and elbow joints, we used a device that consisted of two wooden plates joined at one end with a protractor attached to the hinge. A straight line drawn from the center of the protractor on the side of the movable plate was used to position the movable plate to a predefined angle relative to the other one. The protractor was marked every 0.5°. We estimated the error in presenting the stimulus to be within $\pm(0.25)°$. For the shoulder joint, the subject was asked to extend the arm either to the side or in front of the torso. A digital angle meter (accurate to 0.2°) was used to measure the angle between the fully-extended arm and the horizon. The experimenter lifted the subject's arm to one of the two positions to be discriminated. We estimated the positioning error in this case to be within $\pm(0.2)°$.

Four conditions were tested: wrist, elbow, and shoulder (with arm extended to the side or in front of the torso). Three subjects (both male and female) were tested for each condition. The JND for each subject and each experimental condition was estimated from 100 trials. Average results are summarized in Table 2. Each entry was averaged from three subjects. It is clear that JND decreased from 2.0° at the wrist and elbow joints to 0.8° at the shoulder joint. Considering the fact that joint angle JND is 2.5° at the PIP and MCP joints (RLE Progress Report, 1992), we conclude that proximal joints are more accurate in sensing joint angles than distal ones. However, when performance is defined in terms of endpoint (i.e., the fingertip) resolution, proximal joints are less accurate.

TABLE 2.
AVERAGE JOINT ANGLE JNDs FOR THE WRIST, ELBOW AND SHOULDER JOINTS.

Wrist	Elbow	Shoulder (side)	Shoulder (front)
2.0°	2.0°	0.8°	0.8°

3.3 Stiffness

The purpose of this study was to find out the minimum stiffness required to simulate a rigid object (e.g., a wall) without visual feedback. A rectangular aluminum beam was clamped at one end with the other end free (i.e., a horizontal cantilever as shown in Fig.2: approximately 100 *cm* long, width $h = 0.95$ *cm*, and depth $b = 4.8$ *cm*). The subjects closed their eyes and pressed on the wider surface (i.e. b) at points along the length of the beam until they found the furthest point away from the clamped end where the beam still felt rigid. Anchor and contact points were carefully controlled in a way similar to that discussed in Section 3.4. The distance l between the clamped end and this point was then measured. The typical strategy used by the subjects was to press at various locations back and forth along the beam length before more careful probing was done within a 3 cm distance.

Two male and one female subjects were tested with the following joints individually activated in separate trials: PIP (flex), MCP (flex), wrist (flex and extend), elbow (flex and extend), and shoulder (arm extended in front of, or to the side of the torso, pushing up and down). Anchor and contact points were carefully controlled (e.g., when PIP joint was tested, the proximal phalanx was supported by a flat surface, and the subject pressed the beam with the fingertip by flexing the PIP joint). Each subject did three trials for each of the 10 experimental conditions. The distances from the clamp to the threshold point (i.e., l values) were recorded. The l values averaged over all 90 datum points (3 subjects $\times$ 3 trials per subject $\times$ 10 conditions) turned out to be 31.0 *cm* with a standard deviation of 5.1 *cm*. There seemed to be no significant differences across subjects and joints tested. The stiffness at the "threshold point" (i.e., K) was computed using the equation from elastic beam theory.

Given the average l,

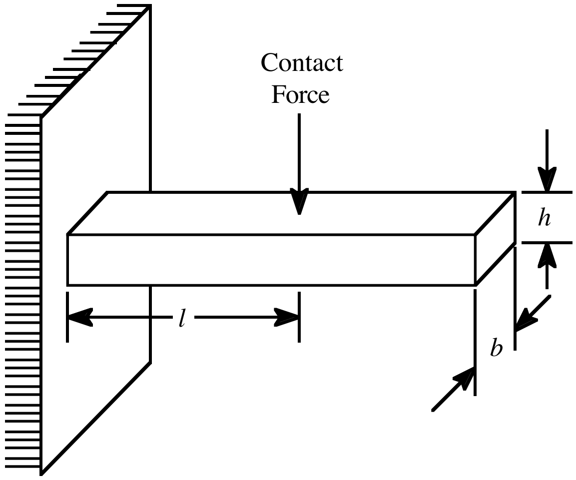

FIGURE 2.
EXPERIMENTAL SETUP FOR STIFFNESS STUDY.

$$\text{average } K = \frac{Ebh^3}{4l^3} = 242 \ (Newton/cm),$$

where Young's modulus

$$E = 70 \times 10^5 \left(newton/cm^2\right) \text{ for Aluminum \#6061.}$$

Given the range of l (i.e., 31.0±5.1 *cm*), the range of K was 153 to 415 *Newton/cm*.

We checked the above results with a different aluminum beam (b = 5.1 *cm* and h = 0.64 *cm*) which had nearly a third the bending stiffness, and obtained similar results for K.

One potential problem with the setup of the stiffness experiment is that as l increased, the bending stiffness of the aluminum beam decreased at a function of $1/l^3$. This non-uniform distribution of stiffness might have limited the resolution of our measurements.

It is interesting to note that when a subject had reached the "threshold point" where the beam still felt rigid, the displacement caused by the probing was visually detectable. Since the subjects' eyes were closed, they were obviously not able to detect this displacement with purely haptic perception.

3.4 Force Output Range

The objective of this study was to establish the maximum *controllable* force humans can produce with joints of the hand and the arm. The force was measured with a load cell (accurate to 0.067 *Newton*) and plotted on a computer screen in real time. To measure the maximum *controllable* force, the subject was asked to exert a maximum force and *maintain* it for 5 *sec*. After several practice trials with visual feedback, the subject was asked to close the eyes and signal when the maximum force had been reached. The experimenter immediately started data collection. The delay between the subject's signaling and the start of data collection was estimated to be 300 to 500 *msec*. The subject was allowed to relax after 5 *sec* of data had been collected.

Two male and one female subject were tested with the following joints: PIP, MCP, wrist, elbow, and shoulder (with arm extended to the side or in front of the torso). Anchor and contact points were carefully controlled (e.g., when elbow

TABLE 3.
AVERAGE MAXIMUM CONTROLLABLE FORCE AND ITS S.D..

		Joint Tested					
Subject	Parameter	PIP	MCP	Wrist	Elbow	Shoulder (side)	Shoulder (front)
Female	force (*N*)	16.5	17.6	35.5	49.1	68.7	87.2
	s.d. (*N*)	0.66	0.79	1.11	1.57	2.52	2.21
	s.d. (%)	*3.99*	*4.50*	*3.12*	*3.19*	*3.67*	*2.54*
Male #1	force (*N*)	41.9	45.1	64.3	98.4	101.5	101.6
	s.d. (*N*)	1.88	2.02	3.23	2.43	0.52	0.47
	s.d. (%)	*4.48*	*4.47*	*5.02*	*2.47*	*0.51*	*0.46*
Male #2	force (*N*)	50.9	42.6	55.5	78.0	102.3	101.7
	s.d. (*N*)	2.16	1.81	1.47	2.18	0.47	0.87
	s.d. (%)	*4.24*	*4.24*	*2.65*	*2.79*	*0.46*	*0.86*

TABLE 4.
AVERAGE FORCE CONTROL RESOLUTION.

		Joint Tested					
Subject	Parameter	PIP	MCP	Wrist	Elbow	Shoulder (side)	Shoulder (front)
Female	Target Force (*N*)	8.9	8.9	17.8	22.2	35.6	44.4
	resolution (*N*)	0.30	0.30	0.35	0.32	0.40	0.43
	resolution (%)	*3.32*	*3.35*	*1.98*	*1.45*	*1.13*	*0.96*
Male#1	Target Force (*N*)	22.2	22.2	31.1	48.9	48.9	48.9
	resolution (*N*)	0.22	0.28	0.33	0.46	0.43	0.39
	resolution (%)	*1.00*	*1.27*	*1.05*	*0.94*	*0.88*	*0.79*
Male#2	Target Force (*N*)	22.2	22.2	26.7	35.6	48.9	48.9
	resolution (*N*)	0.35	0.30	0.34	0.52	0.35	0.43
	resolution (%)	*1.56*	*1.33*	*1.27*	*1.46*	*0.71*	*0.88*

joint was tested, the ulnar side of the elbow was supported by a flat surface, and the ulnar side of the wrist was used to press on the load cell). In general, the fingertip pressed on the load cell when the PIP, MCP, and the wrist joints were tested. Dorsal side of the elbow pressed on the load cell when the shoulder joint was tested. A total of three trials were conducted for each subject and joint configuration. Subjects were allowed to rest between trials. Table 3 summarizes average maximum controllable force and its standard deviation (s.d.). Each entry was averaged over three trials. Several observations could be made from these results. First, the maximum controllable force ranged from 16.5 to 102.3 *Newtons* and increased from the most distal joint (i.e., PIP) to the most proximal joint (i.e., shoulder), except for subject Male#2's average at MCP. Second, for the subjects tested, the female subject consistently achieved smaller maximum controllable force than the male subjects; and the gender differences in force output diminished from PIP joint (16.5 *Newtons* for female *vs.* 41.9 - 50.9 *Newtons* for males) to shoulder joints (87.2 *Newtons* for female *vs.* 101.6 - 102.3 *Newtons* for males). The female subject was of petite size, thus the above gender differences should not be generalized without more evidence. Third, the two male subjects had very good control over force output with the shoulder joint as reflected by the corresponding low s.d. scores (0.46 - 0.86%). Their s.d. scores associated with other joints were in the range of 2.47 - 5.02%. Fourth, the absolute values of s.d. showed no clear trend, but its values in percentage decreased from distal to proximal joints. Although this study was designed to measure mainly the maximum controllable force, it could be observed that the s.d. in percentage of mean force decreased as force increased. This general trend was confirmed by the next study on force control resolution.

3.5 Force Output Resolution

The objective of this study was to measure the precision with which humans can produce a mid-range force with joints of the hand and the arm. The setup was the same as that used in the previous study. To measure force control resolution, each subject was asked to track a force that was approximately half the maximum *controllable* force recorded in the earlier study. Subject was given visual feedback throughout the trial. The force sensed by the load cell was monitored for 10 *sec*. The recorded waveform was then edited to discard the initial rising and final falling portions, to obtain a 5 *sec* steady-state waveform. The s.d. of the steady-state waveform was recorded as the resolution in *Newtons*. In all cases, the mean of the 5 *sec* waveform differed from the target force by less than 0.04 *Newton*. Therefore, the resolution in percentage was simply computed by dividing the s.d. with the target force.

The same subjects and joint configurations used in the previous study were used here. A total of three trials were conducted for each subject and joint configuration. Subjects were allowed to rest between trials. Table 4 summarizes average force control resolution. Each entry was averaged over three trials. The average absolute values of resolution was 0.36 *Newton* with a s.d. of 0.07 *Newton*. The resolution in percentage tended to decrease as target force increased from PIP to shoulder joints, and ranged from 3.35 to 0.71%. Srinivasan & Chen (1993) studied force tracking using the index finger with visual feedback. For forces in the range of 0.25 to 1.5 *Newton*, they found that average absolute error remained approximately constant at 0.039±0.006 *Newton*, and were smaller than our results. However, the same errors expressed in percentage ranged from 16 to 3%, and were larger than those found in the present study.

4. DISCUSSION

Traditional psychophysical studies are based on a coherent set of questions aimed at improving our understanding of human perception and performance. Typically, long-term studies are needed to answer such questions. In contrast, human factors data for the design of specific devices needs to be organized around the desired design specifications, and are required to be generated within a relatively short time. Although the methodology for the experiments and the desired robustness in the data are the same in the two cases, the differences in the goals and the time-scales has caused difficulties in collaboration between psychophysicists and device designers. This study is offered as an example of suitable compromise, where traditional psychophysical methodology was employed and enough number of trials were administered to ensure robust results, but the choice of testing conditions were carefully organized to provide specific data relevant to the design of force-reflecting haptic interfaces. Also, in the interest of time, the parameter space of the stimuli was explored only to the extent that was consistent with our goals. We believe that by focusing on the goals and restricting the scope of the experiments, it is possible to satisfy the rigor of Psychophysics and yet produce useful results within the short turn-around time available for device designers.

We now discuss the implications of the results described in this paper to the design of devices. The pressure perception study reveals that humans are less sensitive to pressure changes (i.e., force changes, when contact area is fixed) when contact area is decreased. Further analysis suggests that the JND for weight per perimeter might be a constant around the forearm area, thus people are less sensitive to overall weight or force changes when the total perimeter is increased. Therefore, we conclude that the contact area at the attachment points of exoskeletons for mechanical ground should be minimized and the perimeter of the area should be maximized, in order to improve the illusion of true grounding.

We showed that joint angle resolution was better at proximal joints than at distal ones. Such characteristics help humans to control end points (i.e., fingertips) accurately. For instance, an error of 1° in shoulder joint angle sensing would result in an error of 1 *cm* at the index fingertip (assuming that the distance from the shoulder joint to the index fingertip is 64 *cm*) whereas the same error in sensing the PIP joint of the hand would only affect the fingertip position by 0.08 *cm* (assuming that the distance from the index PIP joint to the index fingertip is 5 *cm*). Therefore, if one were to have high accuracy in placing an end point of a serial linkage system, the joint further away from the end point should have better accuracy in sensing its own angular position.

The minimum stiffness required to simulate a hard wall obtained from our stiffness perception study presents a real challenge to mechanical design. We know of few devices that are capable of achieving a stiffness of 242 *Newton/cm*. However, when no visual feedback is available, people sometimes fail to differentiate the deformation of soft tissues of the fingerpad from sub-threshold movements of finger joints. A virtual environment simulation can take advantage of this phenomenon by the proper coordination of visual and force feedback. Suppose the human operator wears a force-reflective device and grabs a virtual rigid-object. Although the stiffness of the device will allow the operator's fingers to penetrate the rigid object, the visual display should not show such movements after the virtual fingers made their initial contacts with the virtual object. This will facilitate the simulation of rigidity with smaller stiffness. Perhaps the illusion of rigidity can be further augmented with suitable crisp sound of contact displayed to the user.

Finally, the maximum controllable force for various joint configurations obtained from the force control range study varies from 16.5 to 102.3 *Newtons* and increases from the most distal joint (i.e., PIP) to the most proximal joint (i.e., shoulder). The force control resolution decreases from 1.96% to 0.87% from PIP to shoulder joints and its absolute value stays around 0.36 *Newton*, suggesting that subjects have better control (in terms of percentage increment) over force output with the shoulder joint than the finger joints. These numbers provide the basic information for setting actuator output range and resolution of a force-reflecting device at various joints of the hand and the arm.

These psychophysical experiments not only provide human factors data for the design of force-reflecting haptic displays, but also guide future studies to further resolve some of the issues raised by these data. For example, the invariance of the weight per perimeter JND can be explored in more detail by using objects with the same contact areas, but with different perimeters. In the future, we plan to develop a more detailed catalog of human factors data to aid better design and evaluation of haptic interfaces.

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