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MANUAL RESOLUTION OF COMPLIANCE WHEN WORK AND FORCE CUES ARE MINIMIZED

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ABSTRACT

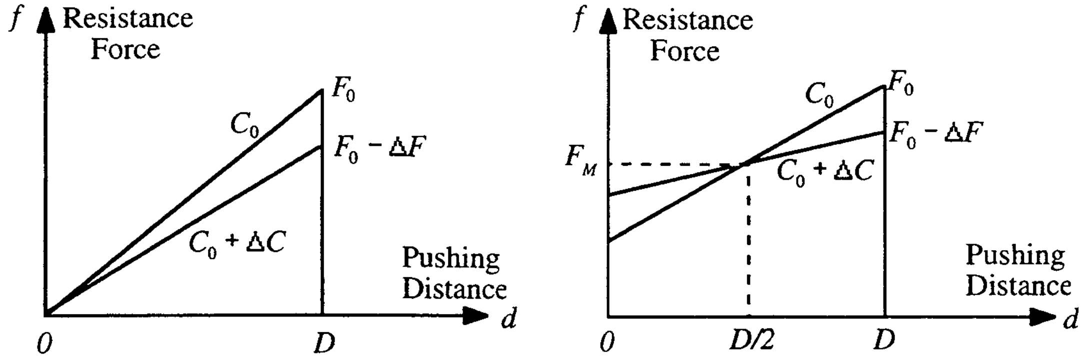
This paper summarizes new experiments on compliance discrimination in which work cues were eliminated and force cues were minimized. The average JNDs for compliance ranged from 15% to 99% and were much larger than the average JND (8%, see Tan, Pang & Durlach, 1992) obtained from previous compliance discrimination experiments in which both work and terminal force cues, as well as compliance cues, were available to the subject. By converting results to corresponding JNDs in terminal force, we obtained a force JND of 5.2% ±0.8%; this value was found to be consistent with force JNDs (6-8%, see Pang, Tan & Durlach, 1991; Tan et al., 1992) we had obtained earlier from force discrimination experiments. We conclude from these compliance experiments and our previous experiments on force and compliance perception that manual resolution of compliance deteriorates when force and/or work cues are reduced or eliminated.

INTRODUCTION

Our interest in the study of manual resolution of physical parameters such as length, force, and compliance are twofold: (1) we want to measure how well humans can discriminate these parameters and thus understand performance in manual object recognition; (2) we want to apply the knowledge gained from these psychophysical studies to the design of better haptic interfaces. When one designs and constructs haptic interfaces for teleoperation or virtual environment systems, it is important to match the resolution of the haptic display to that of the human sensory systems. Compliance is one of the many important object properties (others are shape, mass, viscosity) that can be effectively perceived through the sense of touch. For example, a telediagnostic interface requires realistic display of compliance during palpation. Compliances associated with normal and abnormal health conditions as revealed from palpation should be displayed in a manner that facilitates easy discrimination by the physician at the remote site. In general, our continuing work on manual resolution of object properties provides quantitative guidelines for engineering design. Our earlier work can be found in Durlach, Delhorne, Wong, Ko, Rabinowitz & Hollerbach (1989; length resolution), Pang et al. (1991; force resolution), and Tan et al. (1992; a review).

In an earlier paper (Tan et al., 1992), we reported the degrading effect of roving displacement on both force and compliance discrimination. Average compliance JNDs (just-noticeable-differences) were 22% and 8% for roving and fixed-displacement experiments, respectively. Average force JNDs were 14% and 6% for roving and fixed-displacement experiments, respectively. Further analysis of the data from both force and compliance experiments with roving-displacement seemed to support a "Work Hypothesis"; i.e., subjects tended to respond "bigger force" or "smaller compliance" when the work involved in the active finger motion was greater than some fixed criterion work value. The data from compliance discrimination experiments with roving-displacement also seemed to be consistent with a "Terminal Force Hypothesis"; i.e., subjects tended to respond "smaller compliance" when the terminal force was greater than some fixed criterion value of force.

In the design of our earlier compliance experiments, resistance force f was related to pushing distance d by $f = d/C$, where C is compliance (see Figure 1A). The terminal force increment $\Delta F/F_0$ was equal to $\Delta C/(C_0 + \Delta C)$. Thus for $\Delta C/C_0$ of 22% and 8% (compliance JNDs for roving and fixed-displacement paradigms), $\Delta F/F_0$ was 18% and 7%. These results were very close to the force JNDs for roving and fixed-displacement paradigms, respectively. Therefore, subjects could have relied on terminal force cues for compliance discrimination with this experimental design. For this force-distance profile, work



1A. $f = d / C$ 1B. $f = F_M + (d - D/2)/C$

Figure 1. Force-distance profiles for earlier (Fig. 1A) and current (Fig. 1B) compliance experiments. C_0 = reference compliance, ΔC = compliance increment, F_0 = terminal force associated with C_0, ΔF = terminal force increment, and F_M = mid-point force.

increment $\Delta W/W_0 = \Delta F/F_0$. Because we have no data on the work JND, it is not clear whether work had also played a role in compliance discrimination.

In order to minimize work and terminal force cues, the compliance experiments reported in this paper used the "equal-work" force-distance profile shown schematically in Figure 1B. In this new paradigm, the work cue was eliminated (i.e., the two stimuli being discriminated required the same amount of work). Also, the initial and terminal force cues could be reduced by increasing mid-point force F_M without changing C_0 and $\Delta C/C_0$. For example, for F_M=6 N, D=20 mm, C_0=4 mm/N and $\Delta C/C_0$ = 20%, $\Delta F/F_0$ was 4.9%. By increasing F_M to 9 N without changing any other parameters, $\Delta F/F_0$ was reduced to 3.6%. These terminal force increments were below the average JND (6%) obtained from force discrimination experiments with fixed-displacement (Pang et al., 1991; Tan et al., 1992). Therefore, if the subject could discriminate the two stimuli well (i.e., if d'>1), then the performance must have relied mainly on compliance cues. The opposite turned out to be true: subjects performed very poorly under these conditions.

METHODS

Experimental Apparatus

A two degree-of-freedom (dof) linear grasper (only 1 dof. was active) was used to deliver stimuli to the subject (for a picture of the device, see Fig. 2 in Tan et al., 1992). The experimental apparatus had two parallel plates, one of which was fixed and the other of which could be moved along a linear track perpendicular to the plates. The subject grasped the two plates between the thumb and index finger (with the thumb on the movable plate) and squeezed the movable plate toward the fixed plate.

A system block diagram for the apparatus is shown in Fig. 2. A dc linear-motion motor served as a back-drivable actuator for the movable finger plate. Control was provided by a TMS320C20 DSP board hosted by an IBM-compatible PC. Force, displacement, and velocity information from sensors attached to the movable finger plate were fed back to the controller through a three-channel, 16-bit A/D converter at 2.5 kHz sampling rate. The force sensor was a BLH semiconductor strain gage, the position sensor a non-contacting FLDT by Sunpower, and the velocity sensor an inductive type from Transducer Systems. In order to eliminate errors in the measurement of the force applied to the movable plated by the thumb, a cylindrical roller mounted on the movable plate served as a contact point for the thumb (see Fig. 2 in Tan et al., 1992). This not only ensured that the force was always applied at a constant height above the location of the force sensor in the plate (so that the effective lever arm length remained constant), but also that the force was always applied in the direction perpendicular to the plate in the vertical plane.

The control signal was delivered to the actuator through a 16-bit D/A converter and a Techron dc power amplifier, which acted as a voltage-controlled current source. Except for the motor, all components in the control loop had a wide bandwidth and linearity range. The force/current gain of the motor was approximately constant over a stroke range of 55 mm. Within this stroke range, the motor could be modeled as a second-order system up to 200 Hz. The motor system function had a constant magnitude up to 20 Hz and a strong resonance at around 50 Hz. The friction force of the motor finger interface assembly was both position and direction dependent, but always less than 1 N. The cascaded noise level from the force sensor and the A/D converter was less than 0.05 N.

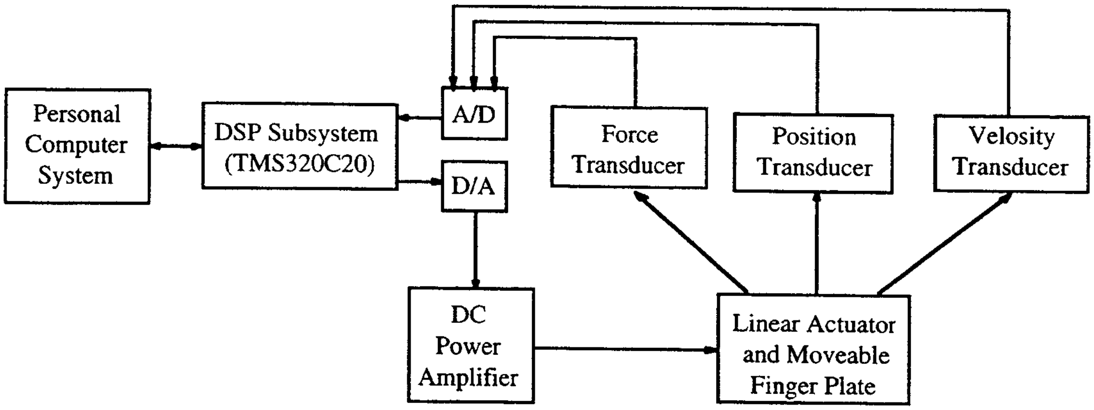


Figure 2. System diagram of the experimental apparatus.

Force control was accomplished with acceleration compensation. In other words, when the subject pushed the finger plate with an acceleration, the acceleration component in the total force felt by the subject was measured and subtracted from the total force so that the force presented to the subject remained constant, independently of how fast the subject pushed, up to the effective closed-loop bandwidth of the system (>10 *Hz*). The range of force was 2-30 *N*, with a resolution of 0.05 *N*. The difference between the specified force and the actual steady-state force was less than 3%.

To ensure the accuracy of the force-distance profiles, two features were checked regularly: (1) the linearity of the profile, and (2) the initial and terminal force values. Linearity was checked with a digital oscilloscope (Hewlett Packard 54501A) by displaying force sensor voltage vs. position transducer output. Initial and terminal force values were measured with a digital force gauge (Chatillon Model DFG). Whenever the measurements deviated significantly from the theoretical calculations, the position and force transducers were recalibrated.

Psychophysical Methods

All experiments used a one-interval two-alternative forced-choice discrimination paradigm with trial-by-trial correct-answer feedback. For each experiment: (a) there were two admissible compliance values C_0 (the reference compliance) and $C_0+\Delta C$ (the reference compliance plus increment); (b) there were two admissible responses "1" and "2"; (c) on each trial, the experimental apparatus presented C_0 or $C_0+\Delta C$ randomly with equal *a priori* probabilities; (d) the subject was asked to imagine a spring being compressed between the thumb and the index finger, and to type "1" for the softer spring (i.e., $C_0+\Delta C$) and "2" for the harder spring (i.e., C_0); (e) the feedback ("right" or "wrong") was displayed on the computer screen after each response.

Table 1 lists all the conditions tested. Four compliance increments ($\Delta C/C_0$) were used for each experimental condition. The increments were different for different experimental conditions, and were chosen such that the percent correct scores varied from ≈60% to ≈90%. For each combination of C_0, D, F_M and $\Delta C/C_0$, 128 trials were collected. A total of 512 trials were collected for each condition from which the JND and response bias β were computed (see Tan et al., 1992 for a description of the data processing scheme).

Table 1. Experimental conditions.

Reference Compliance C_0 (mm/N)	**Pushing Distance** D (mm)	**Mid-Point Force** F_M (N)
2	10	4, 6, 9
4	10	3, 6, 9
	20	4, 6, 9
	30	6, 9
6	10	3, 6, 9
	20	4, 6, 9
	30	4, 6, 9
8	10	3, 6, 9
	20	3, 6, 9
	30	4, 7, 10

Subjects

Three subjects, two females and one male, with no known tactual impairment, participated in this study. The male subject is blind and he participated in our earlier studies on force and compliance perception.

RESULTS

Compliance JNDs

Average compliance JNDs obtained using the "equal-work" paradigm ranged from 15% to 99% (see Fig. 3). With no work

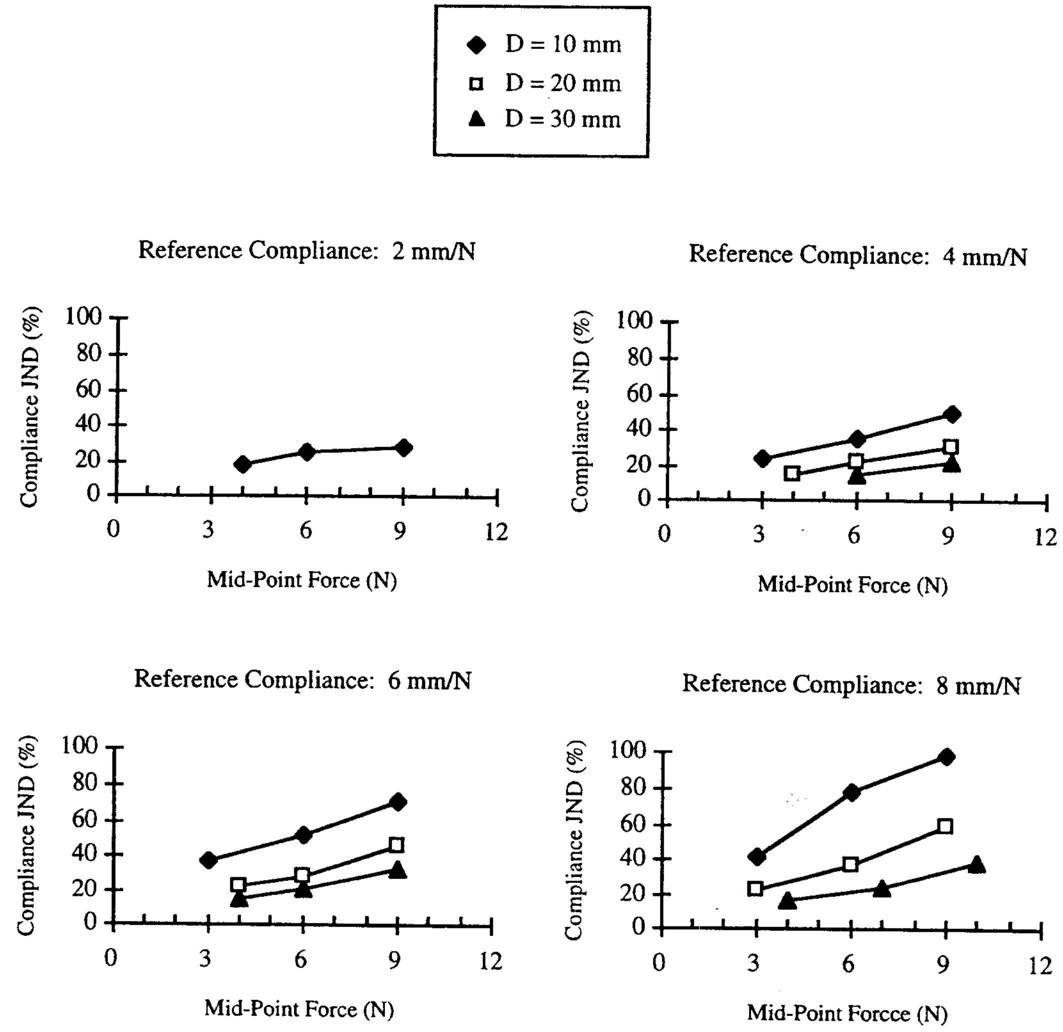


Figure 3. Compliance JNDs averaged over subjects. Each datum point was computed from 1,536 trials.

cues and minimal terminal force cues, these JNDs were much larger than the average JND (6-8%, Tan et al., 1992) obtained from compliance discrimination experiments with fixed-displacement where both work and terminal force cues, as well as compliance cues, were available to the subject.

Several observations are noteworthy from these results. First, for a fixed reference compliance C_0 and pushing distance D, the compliance JND increased monotonically with mid-point force F_M. Second, for a fixed F_M and D, the compliance JND increased monotonically with C_0. Third, for a fixed C_0 and F_M, the compliance JND decreased monotonically with pushing distance D.

Finally, response biases (not shown) were near zero for all the "equal-work" compliance discrimination experiments. This fact, combined with the observed dependence of bias on the displacement D in the previously performed (Tan et al., 1992) roving-displacement compliance and force discrimination experiments (a dependence that could be explained by the associated variations in work when D was varied), lends further support to the "Work Hypothesis".

Terminal Force JNDs

The above results can be greatly simplified if the compliance JNDs are converted to corresponding terminal force JNDs (i.e., convert $\Delta C/C_0$ to $\Delta F/F_0$ in Figure 1B). The resulting average terminal force JND is 5.15% with a standard deviation of 0.76% (averaged over all three subjects and the 29 experimental conditions listed in Table 1). This value is similar to the average JND (6-8%) obtained from earlier experiments on force discrimination with fixed-displacement (Tan et al., 1992). Thus when no work cues are available, subjects appear to rely on terminal force cues to perform compliance discrimination tasks.

Initial Force JNDs

From Figure 1B, it is clear that the *initial* force increment was always equal to the corresponding *terminal* force increment ΔF. Therefore, the initial force JND was related to the terminal force JND by the ratios of terminal over initial forces associated with the reference compliance. These ratios ranged from 1.15 to 4.33 across experimental conditions. As a result, one number with small standard deviation could not be obtained for the initial force JNDs derived from the measured compliance JNDs, and it appears unlikely that the initial force cues played a major role in compliance discrimination.

DISCUSSION

The results that we have obtained with the "equal-work" paradigm, namely, compliance JNDs in the range 15-99%, support previous findings that the compliance JND is poor when work cues and terminal force cues are eliminated or reduced. Furthermore, our results can be parsimoniously explained by assuming that the subjects made use of terminal force cues in these experiments. Under this assumption, all our data can be predicted using force JNDs in the range 5.2% ±0.8%. Apparently, if we had somehow managed to reduce the terminal force cues even further (e.g., by increasing the value of F_M even further), the measured compliance JNDs would have been even worse.

Further interesting issues concerning our results involve comparisons with the data on force and stiffness JNDs obtained by Jones and Hunter (Jones, 1989; Jones and Hunter, 1990 & 1992). In their experiments, contralateral limb-matching procedures were used to measure Weber fractions for force (Jones, 1989) and stiffness (Jones and Hunter, 1990). Stimuli were applied to the arm (engaging mainly the elbow flexor muscles) through an attachment on the subject's wrist.

Superficially at least, our data and those of Jones and Hunter appear relatively consistent. Despite difference in the body components tested and the psychophysical methods employed in these tests, both sets of data indicate force JNDs of roughly 6-8% and larger stiffness/compliance JNDs (stiffness: 23%, Jones and Hunter, 1992; compliance: 15-99%, present study). However, this picture suffers from two major problems. First, it ignores the large force JND, roughly 14%, that we obtained when the displacement D was randomized. According to our findings, at least one factor underlying this large force JND is the tendency to judge work rather than force, even when instructions and feedback are designed for force discrimination. Second, in view of the results obtained in our studies, we do not understand why Jones and Hunter found the force JND to be so much smaller than the stiffness JND. To the extent that one can equate the limb-matching procedure used in their studies to the fixed-displacement paradigm used in our studies, the stiffness JND, as well as the force JND, should have been relatively small. On the other hand, to the extent that one equate their limb matching procedure to our roving-displacement paradigm, the force JND, as well as the stiffness JND, should have been large. In other words, we do not yet understand why changing the body components and psychophysical methods from those used in our studies to those used in their studies should have a different effect on stiffness than on force.

A further question that arises in comparing the two sets of studies concerns the range of compliance/stiffness JNDs obtained in the two cases. Note that the difference in the range of JNDs is not likely the result of the difference in the range of compliance/stiffness used, nor can it be accommodated by converting stiffness JNDs to compliance JNDs or vice versa. Note also that the large range of compliance JNDs obtained in our present study was not due to inter-subject differences: each of the three subjects tested exhibited a large range of compliance JNDs.

In the future, we intend to (1) investigate the issues raised above further; (2) study manual resolution of other parameters, e.g., viscosity and inertia; and (3) measure compliance JNDs associated with compliant objects having compliant surfaces. Both our experiments and those of Jones and Hunter simulated a rigid surface attached to a compliant object. Srinivasan and LaMotte (1993) recently studied softness perception with fingerpads using compliant objects with compliant as well as rigid surfaces. By controlling active / passive touch and the presence / absence of cutaneous cues (via local anesthesia), they were able to study softness perception with both cutaneous and kinesthetic cues (active touch), kinesthetic cues alone (active touch with local anesthesia), and cutaneous cues alone (passive touch). They concluded that cutaneous information alone was sufficient for softness perception when the object surface was deformable; and that kinesthetic information alone was insufficient when the object surface was either deformable or rigid. When both cutaneous and kinesthetic information were available, subjects performed better with deformable than with rigid surfaces.

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