DESIGNING HAPTIC INTERFACES FOR TELEOPERATIONAL AND VIRTUAL ENVIRONMENTS: SHOULD SPATIALLY DISTRIBUTED FORCES BE DISPLAYED TO THE FINGERTIP?

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ABSTRACT

The current study evaluated the role of spatially distributed fingertip forces in the performance of a set of sensory (force detection, spatial acuity, vibrotactile detection) and perceptual (roughness perception, 2D edge orientation, and 3D bump detection via fingertip palpation) tasks. Vision was not permitted. Each task was performed with and without spatially distributed, fingertip-force information. The elimination of such spatial cues substantially impaired performance of all but the vibrotactile-detection and roughness-perception tasks. Despite some decline in roughness perception, subjects were still able to perform related tasks reasonably well. The results offer scientific support for incorporating spatially distributed, fingertip-force information in the design of dextrous haptic interfaces.

Until very recently, most designers of haptic interfaces have elected not to display fingertip forces to the hands of a human operator working within real or simulated remote environments. There are likely different reasons for this. For example, for many early telerobotic applications (e.g., automated manufacturing), it is not obvious that tactile feedback is crucial to good human performance. Nor has the relevant scientific work been conducted to evaluate the potential role of tactile and haptic feedback. Without it, designers may well feel justified in playing down the need to solve the enormous technological challenges inherent in creating tactile sensors and stimulators, particularly those that sense or deliver distributed rather than net force.

However, there is a rapidly evolving interest in designing haptic interfaces for a variety of new applications such as minimally invasive surgery, those that require dextrous interactions with real or virtual environments — perception, exploration, grasping and manipulation. In such cases, tactile (cutaneous) and haptic (cutaneous and kinesthetic) feedback may well prove highly valuable. But as already mentioned, relatively little is known about the capabilities and limitations of human tactile and haptic processing.

Informally, we know that tactile feedback is critical for dextrous motor control. When we lose tactile sensations because of peripheral nerve damage to the hand, we often drop things and cannot use some tools properly, for example, we can cut ourselves when trying to use a knife. Neurophysiological investigations by Johansson and his colleagues (e.g., Westling & Johansson, 1984) have confirmed the importance of cutaneous feedback in order to avoid slip during precision grasping with thumb and forefinger.

The current paper reports the results of a comprehensive behavioral investigation of the potential value of sensing and displaying fingertip tactile information via haptic interface systems. We have chosen to focus specifically on the contribution of spatially distributed fingertip forces to human performance. Should spatial tactile information (which refers specifically to array force as opposed to net force) prove neither critical nor highly beneficial, then designers may rest assured that there is little need to develop complex new tactile technologies. If, on the other hand, we find that performance is substantially impaired by eliminating spatial tactile feedback, then it provides a strong impetus for trying to find ways in which such information may be delivered to the operator's hand.

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The value of spatially distributed cues was assessed empirically with a variety of tools used by psychophysicists. For each psychophysical task, we compared performance using two modes of tactile sensing.

In the "sheath" (experimental) condition, observers used what we intended as one of the simplest of teleoperational systems—a rigid fiberglass sheath, molded to the shape of the fingertip, was worn to simulate conditions that would occur during remote sensing with force feedback only. The sheath's rigidity served to eliminate the normal correlation between the geometric properties of the contacted surface and the pattern of spatially distributed forces on the fingertip. The outer surface was covered with a very thin (1 mm) foam tape to prevent "chatter" during initial contact. The sheath was held firmly in place by a finger section cut from a latex surgical glove, as shown in Figure 1. The support added negligible load, while permitting good motor dexterity.

![Figure 1: Molded Sheath Supported by a Finger Section from a Fitted Latex Surgical Glove](image)

In the "no sheath" (control) condition, observers wore just the latex fingertip cover, to equate friction across conditions. Each of the tasks that will now be described was performed in both the sheath and no-sheath conditions, in order to assess the contribution of spatially distributed forces on the fingertip, which would be absent when the sheath was worn but present with the gloved finger.

TACTILE SENSITIVITY AND RESOLVING CAPACITY

Force thresholds
To assess sensitivity to intensive variation of tactile stimulation, we measured the minimal force required to just detect the presence of commercially available nylon monofilaments applied to the distal phalanges of the thumb and index finger. Variation in the diameter of the monofilaments was used to alter the applied force required to just bend the hair.

To determine force thresholds, observers were asked to say whether or not they detected something contacting their fingertip on each stimulus application. They were instructed to say "yes" only when they felt pressure on the fleshy part of their index finger or thumb. A psychophysical technique known as the Method of Limits was used, with both ascending and descending blocks of trials, in conjunction with an adaptive staircase procedure.

We averaged the thresholds collected for the thumb and forefinger (3 apiece), because the patterns were very similar. The mean force thresholds were 0.031 N and 0.054 N for the no-sheath and sheath conditions, respectively. Thus, the elimination of spatially distributed force patterns on the fingertips of both thumb and forefinger produced a 73% decrease in sensitivity to applied force.

Vibrotactile thresholds
The second experiment determined tactile sensitivity to a time-varying component of force, namely, vibration. Vibrotactile thresholds were obtained for the following 5 frequencies: 20, 40, 80, 160 and 320 Hz, using a mini shaker as the vibratory source. The subjects wore a blindfold and headphones, and auditory cues were masked by playing a background tape of white noise. The subject placed his or her right index finger on a contactor mounted on the shaker. Contact force was not controlled, but instead the normal component was measured throughout the trial. A descending Method of Adjustment was used, in which the vibratory signal was initially set well above threshold, and the subject adjusted the amplitude of the vibration with a continuously adjustable control knob, until it was set at the point where it could just no longer be felt. This procedure was repeated twice at each of the 5 frequencies in both sheath and no-sheath conditions.

As commonly found (e.g., Verrillo, 1963), thresholds declined as a function of increasing frequency up to 320 Hz. However, wearing the finger sheath did not influence the vibrotactile threshold, regardless of frequency. Subjects applied more force when the sheath was worn (mean = 0.39 N) than when it was not (mean = 0.21 N). Conceivably, subjects pressed harder to compensate for reduced sensitivity in the sheath condition. However, subjects did not adjust their finger force accordingly in a subsequent texture perception task (see PERCEPTUAL TASKS, Roughness Perception: Numeric estimation of perceived roughness magnitude), which unlike the vibrotactile threshold task did not require such precise fingertip positioning. Therefore, we believe that subjects pressed harder to increase the confidence with which they maintained their finger position on the contactor (see e.g., Westling & Johansson, 1984), rather than to improve their sensitivity.

We conclude that subjects were able to use temporal cues to detect vibratory stimuli about as well when the sheath was worn as when it was not. In the section PERCEPTUAL TASKS, we use this finding to interpret performance of a tactile roughness perception task with spatially distributed force information eliminated via the rigid sheath.

2-point touch thresholds
The spatial resolving power of the fingertip was measured as the 2-point touch threshold, i.e., the minimal spatial separation between two points that was required to reliably differentiate the pattern as two distinct (non-overlapping) contact points.
A custom-designed set of four disks, with stimulus pins protruding from the outer edge of the disks, was produced to determine 2-point touch thresholds. Each stimulus pattern consisted of two metal pins (1 mm dia), with rounded tips. The inter-pin separation distance (centre-to-centre) was increased successively around the disk circumference both within and across the four stimulus disks. Across the full stimulus set, interpin distance increased from 0 (pin pairs in contact) up to 25 mm. The 2-pin stimuli were applied midway down and along the central longitudinal axis of the volar portion of the distal phalanges of the thumb and index finger. We obtained three threshold estimates for both the sheath and no-sheath conditions, again using the Method of Limits with a single staircase procedure.

The threshold for the no-sheath condition, 3.39 mm (S.E.M. = .05) was substantially lower than that for the sheath condition, 21.81 mm (S.E.M. = .06), regardless of whether the thumb or index finger was used. There was a 6.43-fold decrease (321% decline) in spatial acuity in the absence of spatially distributed force patterns on the skin. In fact, many observers were actually unable to detect two separate points on the finger pad when the maximum separation was used. So we can only set an upper bound on spatial acuity with the sheath and hence may underestimate the magnitude of the impairment caused.

PERCEPTUAL TASKS

Roughness perception

**Numeric estimation of perceived roughness magnitude.** In an initial experiment, subjects were asked to evaluate the perceived roughness of a set of nine raised, 2D dot patterns. These were produced from a corresponding set of black and white spatially jittered dot matrix patterns using the nyloprint photoengraving technique (for details, see Lederman, Thorne and Jones, 1986). Each pattern was derived from a regular dot matrix with a fixed interdot spacing. To produce each of the current stimuli, the position of each dot in the regular matrix was spatially jittered, both angularly and radially, within a polar coordinate system with the centre of the dot at the origin. Angular jitter was specified by randomly selecting 1 of 36 possible 10-degree sectors. Radial jitter was specified by randomly selecting a value ranging from 0 to 50% of the non-jittered interdot spacing (the maximum percentage was determined by the criterion that there be no overlap between adjacent dots). The dot diameter was always 0.34 mm. The resulting pattern reflected random; however, the mean interdot spacing was equal to the fixed interdot spacing for the non-jittered matrix. The 9 mean interdot spacings used in this experiment ranged from 0.500 to 3.500, in 0.375 mm increments.

Subjects used a Magnitude Estimation procedure to judge roughness. This technique required that they choose the number that best reflected the perceived roughness of each surface. The data were first normalized to adjust for differences in the numeric scales selected by the subjects. The psychophysical functions were best fit by power functions with exponents of 1.49 for the no-sheath condition and 1.13 for the sheath condition. Relative magnitude of the exponent was used as a coarse indicator of relative roughness discrimination.

We conclude that with spatially distributed force information eliminated, subjects are less able to resolve differences in the roughness of the surfaces, corresponding more precisely to a 2.3-fold reduction in perceptual differences between stimuli. This value is determined by calculating the antilog of the slope difference of the linear functions that result when the data are plotted on log-log scales. That the sheath exponent was considerably greater than 0, however, indicates that subjects were still able to use the temporal cues to differentiate on the basis of perceived roughness quite well.

**Roughness comparison.** An alternate method for assessing the relative contributions of spatial and temporal information to roughness perception is to ask people to judge which of two surfaces is rougher when the sheath is worn versus when it is not. In the next experiment, the same types of surfaces were used, the range of mean interdot spacings again varying from 0.5 to 3.5 mm. The plates were presented in pairs, so that members of a pair differed in the number of 0.125-mm steps separating them, from 1 to 5 steps.

Overall, subjects demonstrated a small decline in accuracy when the spatially distributed force information was not available. Accuracy scores were compared for sheath versus no-sheath conditions by step size. For 1-step pairs, the no-sheath condition resulted in 70% accuracy, as opposed to 55% for the sheath condition. The no-sheath condition reached 90% accuracy for 3-step pairs, while the sheathed finger attained 83%, with no further improvement for differences greater than 3 steps. Similar experiments that required subjects to explore these same plate pairs with long rigid probes (with different size tips) held in a precision grip indicated slightly better performance than with the sheath. Differences between the two studies are likely due to the mechanical effects of the various linkages (for details, see Klatsky & Lederman, submitted).

Earlier experiments by Lederman and her colleagues (e.g., Lederman, Loonis and Williams, 1982; Lederman, 1983) indicated that people do not normally use vibrotactile information to judge macroscopic roughness (i.e., interdot spacings about 1 mm or more). The current experiments confirm that when information about spatially distributed fingertip forces is eliminated, subjects are capable of using the remaining vibratory cues reasonably effectively. The relatively small deficits observed in the current experiments may be attributed to the loss of the spatial information.

**2D edge orientation.**

The sixth task was selected to assess tactile spatial perception. Observers were required to determine the orientation of a bar (2 mm wide x 10 mm long) applied to the volar portion of the distal phalanx of the right index finger, with versus without the sheath.

The stimuli are shown in Figure 2. Each bar rose 10 mm from a planar base, and was aligned in one of 6 different orientations with respect to a 0-degree axis extending horizontally to the right of the observer: 0, 30, 60, 90, 120 and 150 degrees.
We used a fully automated apparatus (Moore, Broekhoven, Lederman & Ulug, 1991) to deliver the stimuli to the right index finger. The six orientation stimuli were mounted on separate planar facets of a rotating drum. Observers placed their right index finger in a finger rest, horizontally extending the distal pad out beyond the support. The stimulus drum rotated beneath the finger until the desired stimulus faced upward. At a designated time, the drum was raised up to contact the fingertip. Observers maintained static contact with the stimulus until they had made their verbal response, which was recorded by a lapel microphone. There were six such trials at each orientation.

A sheet visually depicted the orientations of the six different stimuli. Beneath each visual pattern was a randomly selected capital letter that was used to indicate the observers’ visual matches. At the end, observers also rated the degree of confidence with which they were able to judge the orientations in the sheath and no-sheath conditions.

The relative accuracy in the no-sheath condition was 78% versus 18% (i.e., at chance) in the sheath condition.

Observers’ confidence ratings further indicated the considerable degree of difficulty in performing the perceived orientation task without spatially distributed force patterns on the skin. Their mean confidence ratings on a scale of 1 (very low) to 10 (very high) were 2.45 and 7.15 for the sheath and no-sheath conditions, respectively, i.e., a 3-fold reduction in confidence.

3D lump detection via fingertip palpation

The seventh task required observers to decide whether or not a rigid mass was embedded in simulated tissue, once again with spatially distributed forces present or absent. This task was designed to emulate the search for a cancerous 3D mass in compressible material (such as partially inflated lung tissue) via palpation.

A single steel ball of varying size was mounted at different positions on the base of a petri dish, which was filled with compressible foam rubber (Figure 3). Observers palpated the "tissue" by applying a force normal to the surface, beginning at the center and moving out toward the edge of the dish in increasingly wider circles. Each ball was only present on half of the trials. Performance was evaluated with and without a sheath being worn on the middle finger.

We only considered the data for the target-present conditions, as those for the target-absent trials were uninformative. Performance was close to 100% in target-absent trials for both finger cover conditions. Clearly, observers were strongly biased to answer "no". With spatially distributed forces removed, there was a decrement in detection performance across all ball sizes. The two functions are well fit by ogives. Using these best fit functions, we determined that a 75% accuracy criterion required diameter values of 4.6 mm and 6.6 mm, for the no-sheath and sheath conditions, respectively. This increase corresponds to a 43.5% decline in performance.

To detect the presence or absence of the 3D masses with no sheath in place, our subjects could have used changing spatial skin deformation patterns, as well as vibrotactile and kinesthetic cues. When the finger was covered with a rigid sheath, only the latter two sources are available. Presumably, the loss of spatially distributed force information accounts for the extent to which performance was impaired.

SUMMARY AND CONCLUSIONS

The current study has evaluated the role of spatially distributed fingertip forces in the performance of a set of sensory and perceptual tasks when such information was either retained or eliminated by wearing a rigid sheath on the fingertip. To date, our results highlight substantial impairment in a number of sensory and related perceptual
tests: sensitivity to minimal force, spatial resolution (2-point touch thresholds), perception of 2D bar orientation, and the detection by palpation of 3D masses embedded in both compressible (and incompressible) materials. These results likely underestimate the full extent of impairment as our "haptic interface," a rigid sheath, is far simpler than any current or future system.

The elimination of spatially distributed forces using the rigid sheaths did not substantially alter vibrotactile thresholds. Moreover, despite some decline in estimating the magnitude of roughness perceived, our subjects were able to do reasonably well in perceptually differentiating surfaces in terms of roughness by using the residual temporal cues available in the vibrations produced by relative motion between sheath and surface. It is known that people normally use intensive or spatial skin deformation cues, when available, to judge macro roughness; however, they can and will apparently use vibrotactile cues as reasonable substitutes for remotely sensing texture.

Table 1. SUMMARY RESULTS OF REMOVING SPATIALLY DISTRIBUTED INFORMATION

<table>
<thead>
<tr>
<th>TASKS</th>
<th>IMPACT ON PERFORMANCE</th>
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<tr>
<td>SENSORY:</td>
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<tr>
<td>Force thresholds</td>
<td>73% decline in threshold</td>
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<tr>
<td>Spatial resolution (2 pt. -touch threshold)</td>
<td>321% decline in threshold</td>
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<tr>
<td>Vibrotactile thresholds</td>
<td>No significant effect</td>
</tr>
<tr>
<td>PERCEPTUAL TASKS:</td>
<td></td>
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<tr>
<td>Roughness estimation (slope)</td>
<td>2.3-fold decline in roughness differentiation</td>
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<tr>
<td>Which is rougher?</td>
<td>21% decline in accuracy</td>
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<tr>
<td>1-step pairs</td>
<td>&lt;1% decline in accuracy</td>
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<tr>
<td>3-step pairs</td>
<td></td>
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<tr>
<td>2D bar orientation</td>
<td>Chance-level matching accuracy</td>
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<tr>
<td>Detection of 3D mass via palpation</td>
<td>150% decline in confidence rating</td>
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<td></td>
<td>45% increase in size of mass detected at 75% accuracy</td>
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A summary of the major findings from our research program is presented in Table 1. Overall, our results suggest there may be significant perceptual costs when spatially distributed fingertip forces are not sensed or displayed to novice operators of teleoperator and virtual environment systems. (We do not include highly practiced operators as we have not as yet specifically evaluated the consequences of extended learning.) In general, cutaneous sensitivity (e.g., as measured by force threshold) is likely to correlate with perceptual and motor tasks that require the remote detection and resolution of net forces rather than spatially distributed force patterns. In contrast, cutaneous spatial acuity (e.g., as measured by 2-point touch) is more likely to interfere with the performance of perceptual and motor tasks that require the spatial processing of small geometric differences (i.e., smaller than the fingertip) and the discrimination of the softness of compliant objects with deformable surfaces (Srinivasan & LaMotte, 1995). Sensitivity to vibrotactile stimulation (as measured by vibrotactile thresholds) is likely to relate to the relative success with which contact can be remotely detected, and to the extent to which surface roughness properties may be differentiated. The kinesthetic system can be used to process relatively larger geometric differences (i.e., larger than fingertip) and the relative softness of compliant objects with rigid surfaces (Srinivasan & LaMotte, 1995).

Current procedures used in minimally invasive surgery only provide the surgeon with visual feedback from small camera systems (e.g., endoscope, laparoscope) about the remote body cavity with which they interact. However, their manipulation tools are not currently equipped with net force, let alone, array force sensors. On the basis of the current psychophysical results, we believe that there would be substantial advantage to adding tactile feedback. Our work offers a scientific basis for recent attempts to develop distributed force-feedback tools (see e.g., Howe, Peine, Kontarinis, and Son, 1995).

A fuller report of methodology, results, and implications for design of haptic interfaces will be provided in a separate journal article.

REFERENCES


Klatzky, R.L. and Lederman, S.J., submitted, "Roughness perception through a rigid link from surface to skin".


