

# Effects of Vision and Friction on Haptic Perception

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**Objective:** Two experiments were conducted to examine the effects of vision and masking friction on contact perception and compliance differentiation thresholds in a simulated tissue-probing task. **Background:** In minimally invasive surgery, the surgeon receives limited haptic feedback because of the current design of the instrumentation and relies on visual feedback to judge the amount of force applied to the tissues. It is suggested that friction forces inherent in the instruments contribute to errors in surgeons' haptic perception. This paper investigated the psychophysics of contact detection and cross-modal sensory processing in the context of minimally invasive surgery. **Method:** A within-subjects repeated measures design was used, with friction, vision, tissue softness, and order of presentation as independent factors, and applied force, detection time, error, and confidence as dependent measures. Eight participants took part in each experiment, with data recorded by a custom force-sensing system. **Results:** In both detection and differentiation tasks, higher thresholds, longer detection times, and more errors were observed when vision was not available. The effect was more pronounced when haptic feedback was masked by friction forces in the surgical device ( $p < .05$ ). **Conclusion:** Visual and haptic feedback were equally important for tissue compliance differentiation. **Application:** A frictionless endoscopic instrument can be designed to restore critical haptic information to surgeons without having to create haptic feedback artificially.

## INTRODUCTION

In many visually guided motor tasks, such as drawing, needlework, automobile driving, and surgery, the importance of tactile and kinesthetic feedback is often underappreciated until it is no longer available. *Tactile feedback* refers to the information about the manipulated object that is obtained through the sense of touch, whereas *kinesthetic feedback* is available through the sense of position and movement. These two general senses make up a person's haptic sense. This research examines the importance of haptic feedback in such cases, using minimally invasive surgery as a model.

Minimally invasive surgery (MIS) differs from open surgery in that instead of one large incision in the patient's body providing direct access for the surgeons' hands, several small incisions allow long, remotely actuated tools and a laparoscope with a miniaturized camera at the end to reach the

surgical site. The advent of MIS has resulted in reduced trauma, shorter hospital stays, and quicker recovery for the patient, but the minimal access to the surgical site has reduced the haptic feedback to the surgeon. Surgeons must be aware of how hard they press on or stretch delicate tissue to keep damage at a minimum. With experience, MIS surgeons have learned to compensate, to a limited extent, for reduced kinesthetic and tactile feedback by relying primarily on visual cues.

However, data in the literature indicate that injury to the bile ducts during cholecystectomy, the removal of a dysfunctional gall bladder, occurs at a rate that is three times higher in laparoscopic surgery (0.3%) than in traditional open surgery (0.1%; Archer, Brown, Smith, Branum, & Hunter, 2001; Strasberg, Hertl, & Soper, 1995; Traverso, 1999). Using the conservative estimate of 500,000 annual laparoscopic surgeries, 1500 patients experience biliary injury. A recent study puts injuries at 2000 per year (Hugh, 2002). Other research

suggests that injury rates have not improved with time or experience (Adamsen et al., 1997).

A recent study by Way et al. (2003) suggests that the misidentification of biliary anatomy stems principally from misperception, not errors of skill, knowledge, or judgment. In 97% of the 252 biliary duct injury cases studied, the surgeon had either (a) seen and deliberately cut a duct that he or she believed to be something else or (b) injured an unseen duct while performing a dissection that he or she believed was a safe distance from the duct. Way et al. (2003) believe that loss of haptic perception is the most important contributor to such errors and that the restoration of haptic cues can help guide the surgeon to the cystic duct when it is otherwise difficult to see or identify.

We believe the lack of haptic feedback in MIS is attributable largely to the instrumentation. The tools are long, placing the surgeons' hands at a distance from the site. The mechanisms that transmit action and reaction are inefficient, allowing slop and damping of interaction forces. In addition, the instruments are inserted into the body cavity through ports, which contain friction seals that fit tightly around the instruments to maintain gas pressure within the body cavity. We believe this last element to be the most important factor affecting feedback during probing tasks.

For a surgeon to get useful force information from the surgical site during probing and dissecting, he or she must be able to accurately differentiate between seal friction and tissue contact. According to Weber's law, the just-noticeable difference in a stimulus is proportional to the magnitude of the original stimulus (Boff & Lincoln, 1988). Because the contact forces between tool and tissue are small relative to the amount of friction in the system, the surgeon may have to press harder in order to perceive a difference in tissue resistance above the level of the friction force from the port. Not only is it more difficult for humans to detect and differentiate individual signals under these conditions, their limited capacity for working memory may be overwhelmed by simultaneous stimuli.

In addition, the improper matching of sensory input to processing modality (i.e., judging force application by watching the endoscopic image as opposed to feeling it) and the use of the visual channel to process increasing amounts of information may be causing inefficiency and competi-

tion for resources. These concepts, which are well established in many domains, may be the cause of the surgeons' difficulties in perceiving and differentiating force feedback during MIS. Deep nerve receptors allow monitoring of joint position and muscle action to judge applied force (kinesthetic feedback), whereas fingertip surface receptors allow sensation of vibration/pulsation, texture, and temperature (tactile feedback). Surgeons use both types of feedback during open procedures to reliably differentiate soft tissue, connective tissue, and pulsing arteries. However, tactile feedback is very difficult to transmit remotely without adding sensors and controllable surfaces, whereas kinesthetic feedback is more easily transmitted through existing rigid tools. Therefore, in this research, we are concerned primarily with kinesthetic feedback as opposed to tactile feedback. We investigate the psychophysics of haptics as predicted by Weber's law and the effects of inefficient information processing in MIS.

Even though surgeons have learned to judge tissue properties and contact pressure in the MIS environment largely by visual observation, research by Klatzky, Lederman, and Matula (1993) indicates that vision is not substitutable for touch. Smyth and Waller (1998) have shown that the visual modality is most efficient for spatial information such as shape and size, whereas the haptic modality is best utilized for force and texture information. In MIS, the surgeon is forced to process both visual and haptic information through the visual channel. Not only is it inefficient for haptic information to be processed in visual working memory, it may be overloading the already limited resources for the visuospatial tasks (Baddeley, 1996). Tissue may appear healthy but in fact be distended and fragile, leading a surgeon to cause inadvertent damage if he or she cannot feel its abnormal texture. The presence of visually obscured but haptically sensed anatomy (i.e., hidden under fatty tissue or other structures) may provide clues about incorrect positioning or unexpected anatomy. The potential for errors and injury is expected to increase with a reduction in the quality of haptic feedback. Bicchi, Canepa, De Rossi, Iacconi, and Scilingo (1996) found a reliability of only 50% for trained participants and 30% for untrained participants using current laparoscopic forceps to sort materials with very different stiffness and damping characteristics. Similarly, research at the

Harvard Biorobotics Lab (Wagner, Stylopoulos, & Howe, 2002) showed that in a dissection task using a robotic system without force feedback, participants increased applied force by 50% and the number of tissue-damaging errors by a factor of 3, when compared with dissecting with force feedback.

We suggest that the poor quality of haptic feedback in current MIS tools, attributable in large part to masking friction in the interface, has degraded the users' ability to accurately perceive contact with tissue. The goals of this research were to examine the relative effects of masking friction and vision on force perception and application. We hypothesized that with friction in the tool interface, force perception threshold would be higher (Hypothesis 1), force application would be less efficient (Hypothesis 2), errors in differentiation would be greater (Hypothesis 3), and participants' confidence in differentiation judgments would be lower (Hypothesis 4). Finally, we hypothesized that visual feedback would provide incremental benefit to the perception of contact but that the combination of force and visual feedback would provide the clearest perception of contact (Hypothesis 5).

Two controlled experiments were conducted to test the hypotheses, using simple probing tasks in a psychophysical paradigm. Both experiments address Hypotheses 1, 2, and 5, and the second experiment also addresses Hypotheses 3 and 4, using a differentiation task. *Force perception threshold* was defined as the minimum force a participant applied to tissues to perceive contact (applied force). *Force application efficiency* was defined as the inverse of the amount of time from making physical contact to when the participant perceives contact (contact time). That is, the longer the contact time, the less efficient the force application.

## EXPERIMENT 1: SIMPLE DETECTION

### Methods

*Participants.* Eight participants (aged 21–29 years, 4 men and 4 women, 7 right-handed and 1 left-handed) with no previous medical training volunteered. The participants were undergraduate and graduate students at Tufts University who provided informed consent.

*Simulated endoscopic environment.* A 5-mm diameter AutoSuture Endo Clinch II grasper (man-

ufactured by US Surgical) and a 5/12-mm convertible trocar/port (manufactured by Origin) set at 5 mm were used. The port was mounted on a guide board to simulate the current MIS setup (friction condition; see Figure 1). In half of the test conditions the port was removed from the setup, allowing the grasper to move freely, simulating a frictionless condition (the “no-friction” condition).

Three visually identical, homogeneous silicone gels (GE Silicones) were used to simulate organic tissue with different compliance (see Figure 2). The hardest gel approximated the compliance of liver tissue at 15 kPa, and the medium and soft gels were two and four times softer, respectively.

An opaque box (simulated abdomen) covered the test site, with access holes only for the tool and a 0° endoscope (US Surgical). A 27-inch (69-cm) Sony color monitor was positioned at eye level for viewing and was turned on or off to control the visual conditions (“blind” and “vision” conditions).

*Force-sensing device and data acquisition.* A custom-built strain-gauge force-sensing device with accuracy of  $\pm 0.003$  N was constructed to

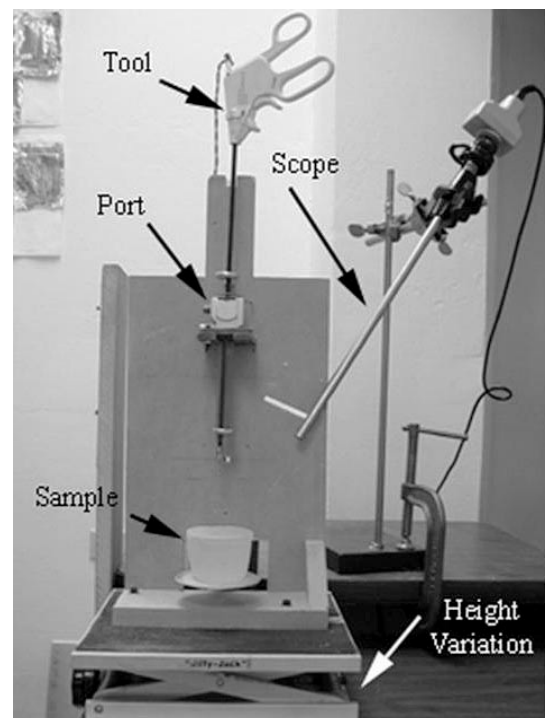


Figure 1. Experimental apparatus for both experiments. All elements were concealed from sight within a box with the exception of the tool handle and the view through the scope.

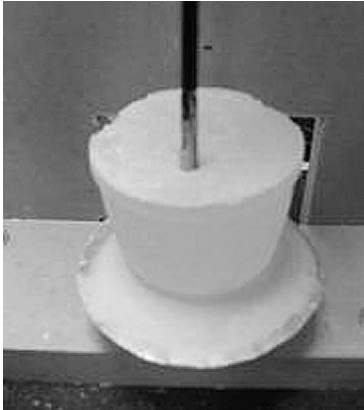


Figure 2. View of contact surface as displayed on the monitor.

record force as a function of time. Data were sampled at 100 Hz, processed by a data acquisition card, and displayed in LabView.

*Test protocol and experimental design.* Participants were allowed to become familiar with the apparatus prior to testing. They were given three practice probes (determined to be an appropriate number during pilot testing) at the beginning of each new condition. Participants were instructed to behave as though the task were actual surgery, probing with just enough force to perceive contact (i.e., as little force as possible) and minimizing the time in contact with the sample. They were pre-

sented with a single simulated tissue sample during each trial. They were instructed to move the tool vertically toward the sample until contact was made. As soon as contact was felt, the participant was to cease pushing, retract the tool, and return it to the supporting stand. The height of the sample was then altered by a random amount between trials to prevent the participants from relying on their memory of sample position. A short break was given between conditions.

A  $2 \times 2 \times 3$  (Vision  $\times$  Friction  $\times$  Softness) within-subjects repeated measures design was used. Each participant completed 10 trials per condition for a total of 120 trials each. The order of tissue presentation was randomized, and the order of vision and friction conditions was counterbalanced.

*Dependent measures.* Applied force and contact time were recorded. Applied force was defined as the maximum force applied to the sample. Contact time was defined as the elapsed time from initial contact until final withdrawal began (see Figure 3).

*Analysis.* Three-way analyses of variance were performed using an alpha value of .05. Preplanned paired sample *t* tests were performed on individual pairs of means in the four Vision  $\times$  Friction conditions (extreme conditions: 1 and 4; blind conditions: 1 and 2; vision conditions: 3 and 4; and intermediate conditions: 2 and 3; see Figure 4). In

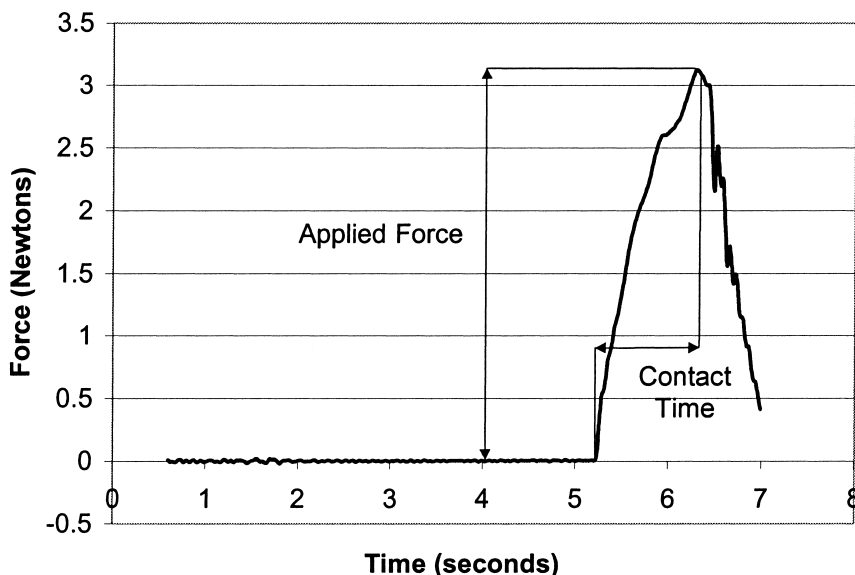


Figure 3. Typical plot of applied force versus contact time.

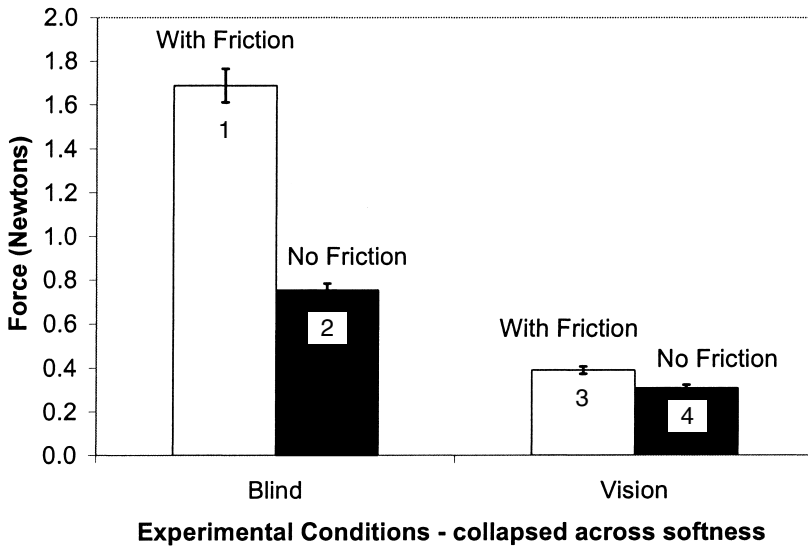


Figure 4. Applied force in simple detection; standard error shown.

Condition 1, participants had no visual feedback (blind) and friction was present in the interface. In Condition 2, participants were blind but friction had been removed from the tool interface. In Condition 3, participants had the benefit of vision but friction was present in the interface. In Condition 4, participants had visual feedback and friction had been removed from the interface. Tukey’s honestly significant difference (HSD) was used as the post hoc test.

**Results**

*Applied force.* There were significant main effects for vision,  $F(1, 79) = 177.6, p < .001$ , friction,  $F(1, 79) = 124.9, p < .001$ , and softness,  $F(2, 158) = 31.2, p < .001$  (see Table 1). When friction was present in the interface, participants applied 26% more force in visual conditions and 126% more force in blind conditions. Comparing extreme conditions in amount and quality of feedback, applied force was 5.5 times higher in the blind-with-friction condition (Condition 1) than in the vision-without-friction condition (Condition 4, see Figure 4). Participants also applied more force to harder samples. The magnitude of forces in this experiment is within the range of those obtained in cadaver urological operations (~0.97 N; Papadopoulos, Vlachos, & Mitropoulos, 2002), suggesting that these measurements are representative of realistic MIS environments. There was a signifi-

cant interaction between vision and friction,  $F(1, 79) = 101.9, p < .001$ , showing that when friction was present there was a larger increase in applied force in the blind conditions than in the vision conditions. Post hoc analysis showed a significant difference between the hard and soft conditions (HSD = 5.0,  $p < .01$ ) and the medium and soft conditions (HSD = 3.6,  $p < .05$ ) but not between the hard and medium conditions.

Paired sample *t* tests of the vision and friction variables showed a significant difference between each of the four pairs of means that were considered: Extreme Conditions 1 and 4,  $t(239) = 19.0, p < .001$ , Blind Conditions 1 and 2,  $t(239) = 14.8, p < .001$ , Vision Conditions 3 and 4,  $t(239) = 5.6, p < .001$ , and Intermediate Conditions 2 and 3,  $t(239) = 15.1, p < .001$ .

*Contact time.* There were significant main effects for vision,  $F(1, 79) = 100.9, p < .001$ , friction,  $F(1, 79) = 203.9, p < .001$ , and softness,  $F(2, 158) = 80.0, p < .001$ . When friction was present in the interface, participants contacted tissues for 39%

TABLE 1: Significant Main Effects in Experiment 1

	Applied Force	Contact Time
Vision	X	X
Friction	X	X
Softness	X	X

longer in visual conditions and 155% longer in blind conditions. Comparing extreme conditions, contact time was 2.9 times longer in the blind-with-friction condition (Condition 1) than in the vision-without-friction condition (Condition 4, see Figure 5). Contact time was shorter for harder samples. There were also significant interactions between the vision and friction variables,  $F(1, 79) = 93.5, p < .001$ , the vision and softness variables,  $F(2, 158) = 61.1, p < .001$ , and the friction and softness variables,  $F(2, 158) = 41.4, p < .001$ . Finally, there was a three-way interaction among the vision, friction, and softness variables,  $F(2, 158) = 50.7, p < .001$ . Post hoc analysis showed a significant difference between the hard and soft conditions (HSD = 11.8,  $p < .01$ ) and the medium and soft conditions (HSD = 10.2,  $p < .01$ ) but not between the hard and medium conditions.

Paired sample  $t$  test analysis of the vision and friction variables showed a significant difference between each of the four pairs of means; Extreme Conditions 1 and 4,  $t(239) = 12.5, p < .001$ , Blind Conditions 1 and 2,  $t(239) = 12.5, p < .001$ , Vision Conditions 3 and 4,  $t(239) = 10.1, p < .001$ , and Intermediate Conditions 2 and 3,  $t(239) = 4.9, p < .001$ .

## Discussion

*Effects of vision and friction.* Results confirmed the hypothesis that friction in the tool interface

would increase the force perception threshold and decrease the efficiency of force application, and the hypothesis that the combination of force feedback and visual feedback would provide the clearest perception of contact (see Figures 4 and 5). When friction was present in the port, participants used more force and took longer to detect contact with tissue.

The resistance from friction was measured at 2.2 N, whereas the average minimum force at which participants could detect contact without the masking effects of friction was only 0.31 N. According to Weber's law in classical psychophysics, the just-noticeable difference (JND) of a stimulus is proportional to the magnitude of the original stimulus (Boff & Lincoln, 1988; see Figure 6). In agreement with Weber's law, participants generated a larger contact force in the presence of friction in order to detect the difference from the original stimulus (i.e., the friction force).

The longer contact times when friction was present show the effects of inefficient information processing. Information is best processed by the appropriate type of working memory, given that humans have specific specialized subsets of memory for visual, auditory, and haptic information (Smyth & Pendleton, 1990; Woodin & Heil, 1996). In the cases when vision was available, the 39% increase in contact time with the presence of friction suggests that processing of haptic information

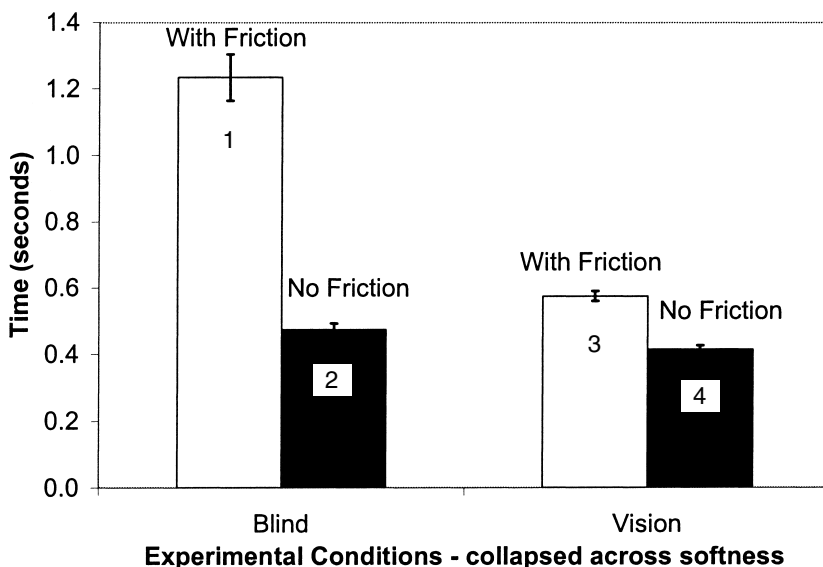


Figure 5. Contact time during simple detection; standard error shown.

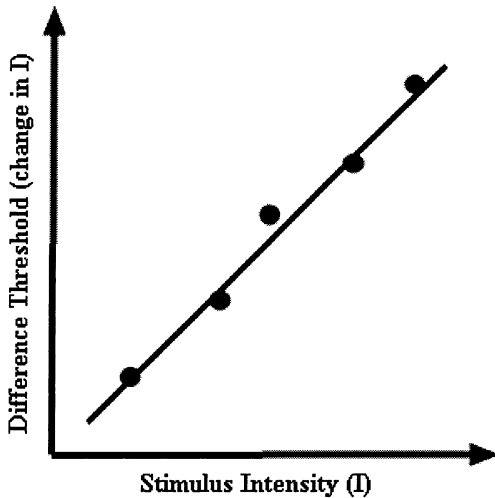


Figure 6. Weber's law (log-log scale): Difference threshold increases with stimulus intensity.

by the visual system is less efficient (Smyth & Waller, 1998).

Visual compensation for inadequate haptic cues is only partially successful. This compensation was helpful in a practical sense but was not as efficient as using the haptic sense to perceive contact force. Meanwhile, in the friction-free conditions, participants were able to use visual information to confirm what they felt, an appropriate and efficient use of both senses. Indeed, the combination of haptic and visual cues in the vision-without-friction condition yielded the lowest applied force and the shortest contact times.

Of practical significance is the fact that the blind condition is representative of real situations in surgery in which the target tissue is obscured from view among other anatomy. In such visually impoverished conditions, the ability to detect tissue contact in spite of the masking friction would be important. It is also possible that errors involving inadvertent damage to tissue just outside the endoscope's field of view would be avoided or, at worst, immediately realized.

The effect of friction was more pronounced in blind conditions (see Figures 4 and 5). This is not to say that haptics was irrelevant when participants were able to see; even with the benefit of vision, they still applied 26% more force and contacted tissue for 39% longer when friction was present. Rather, we suggest that in simple tasks such as contact detection in probing, participants

relied on their visual sense to compensate for the masking effect of friction.

*Effects of softness.* Our results showed that participants applied more force to harder samples but contacted them for less time. Harder materials, by definition, resist deformation more than softer materials do. Reaction force in hard samples rises at a faster rate for a given contact force. Most likely, participants' applied force rose more quickly with the harder samples, and therefore to a higher maximum, before they could stop forward motion after detecting contact. Thus, participants were able to detect harder samples more quickly because the contact force rose to their perception threshold sooner than it did with softer samples.

The detection task in this experiment was relatively simple; participants were able to use visual cues to compensate somewhat for the masking effects of friction. It is expected that the effects of inefficient information processing would be more pronounced during the performance of more difficult tasks. Therefore, Experiment 2 was conducted using a differentiation task.

## EXPERIMENT 2: DIFFERENTIATION

### Methods

*Participants.* Eight participants (aged 21–29 years, 5 men and 3 women, 7 right-handed and 1 left-handed) with no previous medical training volunteered. Participants were undergraduate or graduate students at Tufts University who provided informed consent. None had participated in Experiment 1.

*Simulated endoscopic environment.* The setup was identical to that in Experiment 1.

*Test protocol and experimental design.* As in Experiment 1, participants were allowed to familiarize themselves with the device and practice in each new condition. They were instructed to use only as much force as necessary to determine which sample was softer and to minimize the time in contact with the samples.

Simulated tissues were presented in pairs, one after the other, within a test trial. Participants were not aware that there were only three different samples (i.e., soft, medium, and hard). A total of 12 pairs were compared (soft-soft, soft-hard, soft-medium, medium-soft, medium-medium, medium-hard, hard-soft, hard-medium, hard-hard, soft-soft, medium-medium, hard-hard). The

reason for the repeated like comparisons was to balance the number of the unlike comparisons. Participants were instructed to probe the pair of samples; determine whether the second sample was harder than, softer than, or equal to the first; and rate their confidence in their determination on a 5-point Likert scale with defined numeric intervals as well as text labels.

A  $2 \times 2 \times 12 \times 2$  (Vision  $\times$  Friction  $\times$  Comparisons  $\times$  Order) within-subjects design was used. All participants completed one trial in each of the conditions for a total of 384 comparisons or 768 probes. The order of presentation was randomized across trials, and the order of conditions was counterbalanced between participants.

**Dependent measures.** Applied force and contact time were recorded, as in Experiment 1, for each contact. Responses to the questions (a) "Was the second sample *harder than, softer than, or equal to* the first sample?" and (b) "How confident are you in this judgment?" were also recorded. An error was recorded if the participants' judgment on relative softness was incorrect, (e.g., if a participant reported the second sample to be harder than the first when it was actually equal or softer). Confidence was scored on a 5-point Likert scale ranging from 1 (*not confident*) to 5 (*very confident*).

**Analysis.** Four-way analyses of variance (vision, friction, softness, and order of presentation variables) using an alpha value of .05 were performed for the measures of applied force and contact time. Preplanned paired samples *t* tests were performed between individual pairs of means as in Experiment 1. Tukey's HSD was used as a post hoc test. Two-way analysis of variance (vision and friction variables) using an alpha value of .05 was performed for the measure of error rate. The same preplanned, paired samples *t* tests were performed for the vision and friction conditions.

The nonparametric Friedman test (vision and friction variables) was used for confidence analy-

sis (ordinal data). The nonparametric Wilcoxon signed rank test was used for post hoc analysis of paired conditions. Pearson's correlation coefficient, *r*, was calculated between the variables of judgment confidence and differentiation errors.

## Results

**Applied force.** There were significant main effects for vision,  $F(1, 31) = 51.1, p < .001$ , friction,  $F(1, 31) = 100.1, p < .001$ , softness,  $F(2, 62) = 26.9, p < .001$ , and order,  $F(1, 31) = 9.4, p = .004$  (see Table 2). When friction was present in the interface, participants applied 46% more force in visual conditions and 45% more force in blind conditions. Comparing extreme conditions, applied force was 110% higher in the blind-with-friction condition than in the vision-without-friction condition (see Figure 7). Participants applied more force to harder samples and to the first sample in each comparison pair. There was a significant interaction between vision and softness,  $F(2, 62) = 11.3, p = .002$ , showing that the relative increase in applied force as hardness increased was larger with vision than without it. There were no other two- or three-way interactions. Post hoc analysis of the softness variable showed a significant difference between the hard and soft conditions (HSD = 6.9,  $p < .01$ ) and the medium and soft conditions (HSD = 4.4,  $p < .05$ ) but not between the hard and medium conditions.

Paired samples *t* tests of the  $2 \times 2$  vision and friction matrix showed a significant difference between Extreme Conditions 1 and 4,  $t(191) = 18.6, p < .001$ , Blind Conditions 1 and 2,  $t(191) = 12.6, p < .001$ , and Visual Conditions 3 and 4,  $t(191) = 9.7, p < .001$ . The difference between Intermediate Conditions 2 and 3 was not statistically significant.

**Contact time.** There were significant main effects for friction,  $F(1, 31) = 30.4, p < .001$ , softness,  $F(2, 62) = 5.8, p = .005$ , and order,  $F(1, 31) = 17.1, p < .001$ . When friction was present in the

**TABLE 2:** Significant Main Effects in Experiment 2

	Applied Force	Contact Time	Errors	Confidence
Vision	X	—	X	X
Friction	X	X	X	X
Softness	X	X	—	—
Order	X	X	—	—

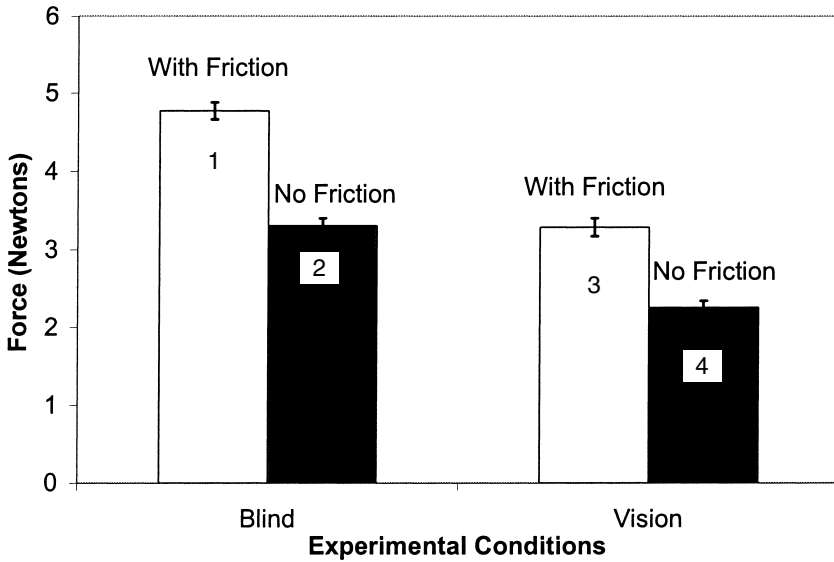


Figure 7. Applied force in differentiation; standard error shown.

interface, participants contacted tissues for 63% longer in visual conditions and 23% longer in blind conditions. Comparing extreme conditions, contact time was 60% longer in the blind-with-friction condition than in the vision-without-friction condition (see Figure 8). Contact time was shorter for harder samples and shorter for the second sample in comparison pairs. There was no effect of vision on contact time. There was a significant interaction

only between the vision and softness variables,  $F(2, 62) = 8.3, p = .002$ . Post hoc analysis showed a significant difference only between the hard and medium conditions ( $HSD = 3.7, p < .05$ ).

Paired samples  $t$  tests of the  $2 \times 2$  vision and friction matrix showed a significant difference between each of the four pairs of means: Extreme Conditions 1 and 4,  $t(191) = 5.9, p < .001$ , Blind Conditions 1 and 2,  $t(191) = 3.5, p = .001$ , Vision

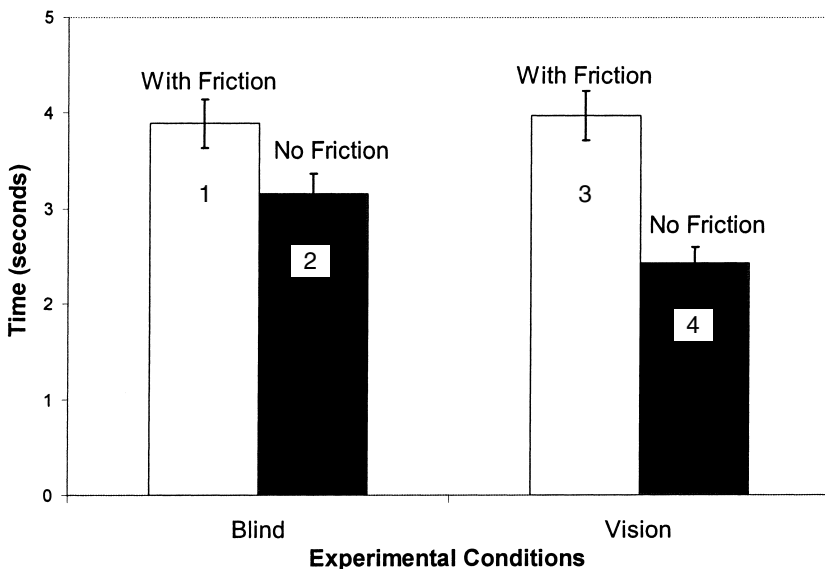


Figure 8. Contact time during differentiation; standard error shown.

Conditions 3 and 4,  $t(191) = 6.6, p < .001$ , and Intermediate Conditions 2 and 3,  $t(191) = 3.3, p = .001$ .

*Judgment errors and confidence.* For errors, there were significant main effects for vision,  $F(1, 7) = 16.7, p = .005$ , and friction,  $F(1, 7) = 7.0, p = .033$ . With vision, the error rate was 9% in the no-friction condition and 33% in the friction condition – 3.6 times higher (see Figure 9). In blind conditions, the error rate was generally higher than in vision conditions and was also higher with friction than without it (a 50% increase). Comparing extreme conditions, the error rate in the blind-with-friction condition was 5.3 times higher than in the vision-without-friction condition. There was no interaction. Paired samples  $t$  tests of the  $2 \times 2$  vision and friction matrix showed a significant difference between Extreme Conditions 1 and 4,  $t(7) = 4.7, p = .002$ , and Blind Conditions 1 and 2,  $t(7) = 2.6, p = .035$ . Neither the Vision Conditions 3 and 4 nor the Intermediate Conditions 2 and 3 showed a statistically significant difference.

For confidence, there were significant main effects of the vision variable,  $\chi^2(1, 191) = 26.0$ , asymptotic significance  $< .001$ , and the friction variable,  $\chi^2(1, 191) = 23.4$ , asymptotic significance  $< .001$ . With vision, confidence was lower when there was friction in the tool/port interface (3.57) than it was without friction (4.11; see Fig-

ure 9). In blind conditions, confidence was generally lower than in the vision conditions and was also lower with friction than without it. The increase in confidence between the two extreme conditions, from blind with friction to vision without friction, was 35%. There was no interaction. Nonparametric paired samples tests of the  $2 \times 2$  vision and friction matrix showed a significant difference between Extreme Conditions 1 and 4,  $Z(95) = -5.5$  based on negative ranks,  $p < .001$ , Blind Conditions 1 and 2,  $Z(95) = -2.7, p = .008$ , and Visual Conditions 3 and 4,  $Z(95) = -4.1, p < .001$ . The means of Intermediate Conditions 2 and 3 were not significantly different.

There was a high correlation between judgment confidence and the percentage of correct differentiations (Pearson's correlation coefficient  $r = .88$ ). There was also a high correlation ( $r = -.98$ ) between feedback and error rate. The error rate decreased as the quality of feedback increased.

**Discussion**

*Effects of vision and friction.* Results of Experiment 2 also supported the hypotheses that friction in the interface would increase the force perception threshold and decrease the efficiency of force application and the hypotheses that the combination of force feedback and visual feedback would

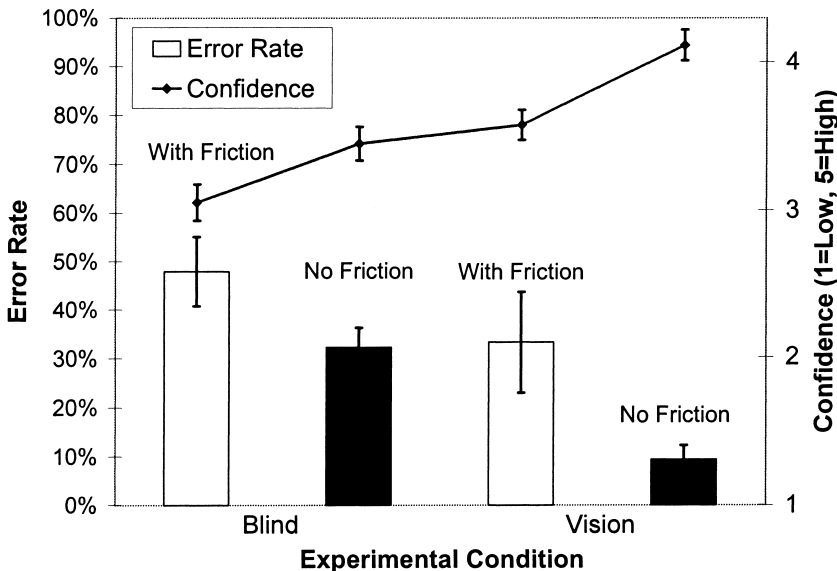


Figure 9. Time spent in contact with tissue when differentiating.

provide the clearest perception of contact (see Figures 7 and 8).

Weber's law was observed to hold for the differentiation task as well. Our findings agree with the results of the study by Wagner et al. (2002), who found a 50% decrease in average applied force in a dissecting task when haptic feedback was *restored* to a robotic surgical tool.

Visual information about the deformation of samples resulted in a mean applied force lower than that without visual information, but it did not reduce the mean amount of time spent in contact with tissue, as it did in Experiment 1. This is the only measure for which vision was not a significant factor. It is proposed that in the more difficult differentiation task, the general benefit gained from vision was mitigated by the decrease in processing efficiency and the increase in resource competition. Participants generally claimed to have never actually felt the samples' properties when friction was present, although they visually perceived the differences. Although vision may provide compensation for missing haptic information in simple probing tasks, it does not provide sufficient compensation in complex differentiation tasks.

*Effects of softness.* As in detection, participants applied more force to harder samples when differentiating but contacted them for less time. With the higher force generation rate in hard samples, participants reached their minimum detectable force sooner, resulting in higher applied force before motion was stopped and in shorter contact times as the perception threshold was reached faster.

*Effects of order.* Participants applied more force to, and spent more time in contact with, the first sample in the comparison pairs. It was originally expected that the second sample would require longer contact time. The logic was that the second sample would require two cognitive processes – an estimate of softness and then a decision on the relative softness – whereas the first sample required only a single estimate of softness and no comparison. However, it appears that perhaps the *first* softness estimation, being an absolute judgment task, was considerably more difficult than the second softness estimation, which was only a relative judgment task.

*Errors in differentiation.* Results supported the hypotheses that friction in the interface would in-

crease the number of errors in differentiation and that the combination of force feedback and visual feedback would provide the clearest perception of contact.

It is interesting to note that participants' performance in the "worst-case" condition, blind with friction, was only marginally better than simple guessing. As there were three choices in each comparison ("harder than," "softer than," or "equal"), random guessing would have produced a 67% error rate (the answer would be correct for one out of every three guesses). The error rate in the blind-with-friction condition was 48%, which is better than guessing, but not by a large amount, especially when compared with the 33% rate for intermediate conditions and the 9% rate in the vision-without-friction condition (see Figure 9).

*Confidence in differentiation.* Results supported the hypothesis that friction in the interface would reduce confidence in differentiation judgments. The strong correlation between confidence and correct answers ( $r = .88$ ) confirmed that the removal of friction, as well as the benefit of vision, improved users' actual performance while also improving confidence in their performance (see Figure 9).

## GENERAL DISCUSSION

The task of differentiation in Experiment 2 was more representative of actual surgery. It required higher applied forces and contact times than did the detection task in Experiment 1. This was true for all experimental conditions, as expected. In the simpler task, detection, it was possible to detect contact by vision alone (although it was easier when combined with the haptic sense). In differentiating, vision alone was not enough to allow participants to accurately sense compliance and differentiate samples.

Presumably, the harder the participants probed and the more time they spent doing so, the greater the amount of information they acquired. Although the effective amount of useful information was the same in all conditions, the higher forces and longer contact times were a result of efforts to overcome the masking effects of friction. The signal-to-noise ratio from modern signal detection theory can be used to model the performance. The sensitivity of the human-tool system was effectively decreased by the presence of "noise"

(i.e., friction). The “signal” from contact with samples was consequently less clear and harder to perceive. Therefore, participants had to adjust their decision criterion (beta) to optimize performance either by probing harder or longer or by risking more errors.

As compared with a laboratory experiment, during actual surgery there is a much higher cost associated with an error. In differentiation of diseased or cancerous tissue from healthy tissue, practicing surgeons would likely set their decision criterion very conservatively to avoid missing a diagnosis. It may be that in practice, as a result of friction in the current instrumentation, surgeons make fewer errors in differentiation at the cost of higher forces and unnecessarily long contact times. In the worst scenario, friction could lead to errors in differentiation because surgeons are unable to perceive differences in tissue compliance. Way et al. (2003) believe that the higher error rates observed in laparoscopic cholecystectomy are a result of impaired haptic feedback, and our results support this hypothesis.

In addition to promoting inefficiency, inappropriate use of sensory modalities could lead to competition for resources in complex or mentally demanding tasks. Both the detection and differentiation tasks were fairly simple when compared with actual surgery, such as suturing or tissue dissection. In MIS, without direct access to the surgical site, the vast majority of information about site interaction must be acquired through the visual modality. There are limits to the capacities of working memory, and when the limits are approached, competition for dwindling resources ensues. It is possible that the performance differences attributable to friction in the tool interface would be even more significant when complex surgical tasks are performed under high cognitive demand and stressful operating room conditions.

### Implications for Design

These results encourage the development of an interface with a cleaner transmission of force feedback that would lead to more efficient information processing and a better “distribution of labor” between the haptic and visual systems. The use of a more intuitive interface in MIS could minimize the negative transfer of skills from those in open surgery. It could also reduce the learning curve for novice surgeons.

The majority of the approaches used by the medical device community to solve the problem of haptic feedback have focused on improving the amount and quality of information in visual displays, artificially creating haptic feedback with software, or improving the responsiveness of the surgical tools themselves. Little has been done in the way of improving the interface between tool and tissue, where a large part of the problem lies. The research presented here indicates the value of an alternative approach in which haptic information would be transmitted directly to the user through the haptic channel instead of through other sensory systems, such as vision. This approach would require a redesigned access port capable of filtering port friction forces from tissue contact forces.

Elimination of friction at the tool/port interface could make MIS more intuitive, reduce the cognitive processing required to align stimulus-response modalities, and improve performance by providing more accurate sensory input. In contrast to the claims of many surgeons that vision is an adequate substitute for haptics, results show that basic force perception and differentiation are fundamentally better when sensory modalities are utilized properly.

### Limitations and Future Research

In this research, the artificial restraint of the port to a guide board for force-measuring purposes is not fully representative of surgery. In actual surgery, the port is supported by the elastic surface of the abdomen, allowing for significant motion in the port. In addition, only one tool/port pair was used. The pair was chosen to be representative of common pairings in the operating room, but results may vary depending on the pairing.

None of the participants tested had any surgical training prior to testing. Some studies in the literature have suggested that surgeons perform better than do nonsurgeons when differentiating soft tissue (Bicchi et al., 1996), whereas others have found that there is no significant difference between the two groups (MacFarlane, Rosen, Hannaford, Pellegrini, & Sinanan, 1999). Although it is true that experienced surgeons may have acquired strategies to overcome, to varying degrees, the effects of friction in the system, the psychophysics of force detection and differentiation examined

here relate to fundamental perceptual abilities that are independent of skill or experience. Other potentially distracting elements from the operating room environment, such as auditory alarms and other personnel activity, were not included in this study. These distractors may play a part in a surgeon's ability to reliably sense tissue contact.

From a theoretical perspective it seems obvious that friction in the interface would affect performance, yet many in the surgical and device manufacturing communities suggest that haptic feedback is unnecessary and a waste of development resources. We maintain that although humans, and MIS surgeons in particular, may be able to compensate to a limited extent for low-quality haptics, their overall performance is degraded and will seriously suffer in high-demand settings. The consistently high rate of patient injury in laparoscopic cholecystectomy is evidence pointing to the possibility of an unsolved issue that may result from poor feedback.

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