

EFFECTS OF FRICTION ON HAPTIC PERCEPTION IN SIMULATED ENDOSCOPIC ENVIRONMENTS

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Current endoscopic instrumentation cannot replicate the haptic feedback available during open surgery. Distracting friction forces in the interface make it difficult for surgeons to detect and differentiate between small-scale surgical site forces. As a result, the visual channel is being used to process information that should be available through the haptic sense. An experiment was conducted to examine the effects of friction, when probing tissues of dissimilar compliance. Results showed that the presence of friction in the interface increased applied force by 45%, contact time by 40%, and errors by a factor of 2 (100%), while its absence increased human operator confidence by 15%. The effects of friction were generally more pronounced in conditions with impaired visual cues but were also very strong when vision was available. These results are applicable to the design of more effective instrumentation for endoscopic surgery as well as robotic surgery.

INTRODUCTION

While the advent of minimally invasive surgery (MIS) has allowed for reduced trauma, shorter hospital stays, and quicker recovery for the patient, the minimal access to the surgical site has reduced the haptic feedback available to the surgeon. Surgeons must be aware of how hard they press on or stretch delicate tissue to avoid causing unnecessary trauma. With experience, MIS surgeons can learn to compensate for reduced kinesthetic and tactile feedback by relying primarily on visual cues, such as visually judging the amount of force applied to tissue based on surface indentation (Cao, Webster, Perreault, Schwaitzberg & Rogers, 2003).

However, data in the literature indicate that injury to the bile ducts during cholecystectomy 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). Studies suggest that the laparoscopic injury rates are not improving with time and experience (Adamsen, Hansen, Funch-Jensen, Schulze, Stage & Wara, 1997). Laparoscopic cholecystectomy is now the most common MIS procedure in the U.S., being performed at a conservative estimate of 500,000 cases annually. A 2002 study estimates injuries at 2000 per year from these procedures (Hugh, 2002).

A study by Way, Stewart, Gantert, Kingsway, Lee, Whang & Hunter (2003) showed that the misidentification of biliary anatomy stemmed principally from misperception, not errors of skill, knowledge, or judgment. In 97% of the 252 biliary duct injury cases studied, the surgeon had either 1) seen and deliberately cut a duct that he believed to be a different duct, or 2) injured an unseen duct while performing a dissection that he believed was a safe distance from the duct. Way and colleagues 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.

In MIS, the lack of haptic feedback is due largely to the instrumentation. MIS 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. Friction introduced by the seals may be an impediment to the transmission of accurate force feedback from the tissue.

For a surgeon to get useful force information from the site, he must be able to accurately differentiate between seal friction and tissue contact. Since 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 friction force from the port. According to Weber's Law, the just-noticeable difference in a stimulus is proportional to the magnitude of the stimulus (Boff & Lincoln, 1988). In surgery, the high level of resistance from friction may dictate that the user must press proportionally harder to notice the difference in resistance when contacting tissue.

In MIS environments, even though surgeons have learned to judge site interactions, tissue properties, and contact pressure largely by visual observation of tissue indentation, research by Klatzky, Lederman & Matula (1993) clearly indicates that vision is not substitutable for touch. Smyth & Waller (1998) have shown that the visual modality is most efficient for spatial information such as shape and size, while 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 kinesthetic information to be processed through the visual working memory, it is overloading the already limited resources for the visual/spatial tasks involved in surgery.

Bicchi, Canepa, De Rossi, Iaconi & Scilingo (1996) found a reliability of only 50% for trained subjects and 30% for untrained subjects when sorting five materials with very

different stiffness and damping factors using current laparoscopic forceps. Similarly, using a robotic system, research at the Harvard Biorobotics Lab (Wagner, Stylopoulos & Howe, 2002) showed that, in a dissection task without force feedback, subjects increased applied force by 50% and the number of tissue-damaging errors by a factor of 3 when compared to performance with force feedback.

The goals of this research were to examine the effect of port seal friction (in the in/out direction) on force application, contact time, and compliance differentiation during simulated laparoscopic surgery. It was hypothesized that applied force and contact time would be reduced when friction was removed from the interface. It was further hypothesized that differentiation of tissue compliance and judgment confidence would be improved when friction was removed.

METHODS

A controlled experiment was conducted to test the hypotheses, using a simple probing task in a psychophysics paradigm.

Subjects

Eight subjects (aged 21 to 28, both right- and left-handed), with no previous medical training volunteered for the experiment.

Apparatus

Simulated Endoscopic Environment. A 5 mm diameter AutoSuture Endo Clinch II grasper was used for the probing task. The grasper was inserted in an Origin 12 mm convertible port (set for use with a 5mm tool), which was mounted to a guide board to simulate the current MIS set-up (Friction condition). Removal of the port from the board eliminated the friction on the grasper (No Friction condition).

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

An opaque box (simulated abdomen) obscured the site, with access holes only for the tool and a US Surgical 0° endoscope. A 27" Sony color monitor was positioned at eye level for viewing and was turned on or off to control the visual condition.

Force-sensing Device and Data Acquisition. A custom-built strain-gauge force-sensing device with accuracy of ± 0.003 N was constructed to record force as a function of time. Force readings were sampled at 100Hz, processed by a data acquisition card, and displayed in LabView.

Test Protocols & Experimental Design

Simulated tissues were presented in pairs, one after the other, within a test trial. Subjects were not aware that there were three different samples (i.e. Soft, Med, and Hard). They 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. Subjects were instructed to behave as though the task were actual surgery, probing with only as much force as necessary and minimising the time in contact with the sample.

A 2x2x12 (vision x friction x comparisons) within-subjects design was used. All subjects completed one trial in each of the conditions for a total of 384 comparisons or 768 probes. Order of presentation was randomized across trials and order of conditions was counterbalanced between subjects.

Dependent Measures

Applied force, contact time, errors, and confidence 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. An error was recorded when the subject incorrectly judged relative softness.

Analysis

Analyses of Variance were performed using an alpha value of 0.05 on the following variables: force, time, errors, confidence, softness, and order. Only the first four are reported in this paper.

RESULTS

Applied Force. Figure 1 shows the mean force applied to tissue samples in contrasting visual and friction conditions (data collapsed across softness). There were significant main effects of both vision ($F(1,767)=51.141, p<0.001$) and friction ($F(1,767)=100.1, p<0.001$) and no interaction between the two.

There was less force applied as the amount of available information increased (examining the bars in Figure 1 from left to right). Subjects applied the most force, 4.77 N, in the blind *with* friction condition. When still blind but *without* friction, applied force dropped to 3.30 N. The applied force was almost identical in the condition with visual cues but *with* friction again. Here the mean was 3.29 N. Finally, subjects applied the least force with vision and *without* friction, a mean of 2.25 N. Comparing the two extreme cases, visual without friction (2.25 N) versus blind with friction (4.77 N), subjects applied over twice as much force.

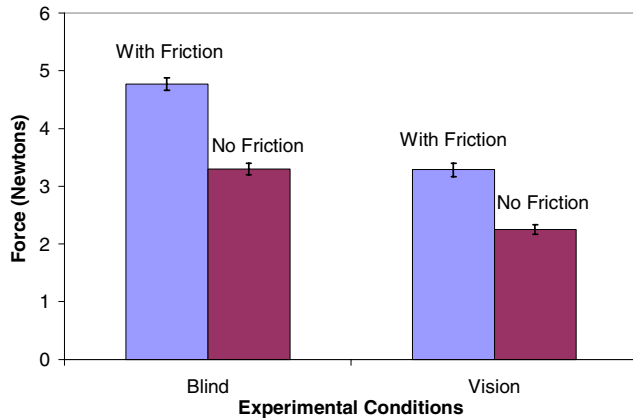


Figure 1. Applied force when differentiating.

Comparing within the blind and vision conditions, the effect of friction was almost the same. Subjects applied approximately 45% more force when friction was present.

Contact Time. When considering contact time during compliance differentiation, there was a significant main effect of friction ($F(1,767)=30.4, p<0.001$) but not vision. Subjects spent less time in contact with tissue samples during conditions without friction in the interface (data collapsed across softness). When blind, subjects contacted tissue for an average of 3.88 sec *with* friction and 3.15 seconds *without* friction. Similarly, with visual cues, subjects contacted tissue for an average of 3.97 sec *with* friction and 2.43 sec *without* friction (see Figure 2). There was no interaction between vision and friction for contact time.

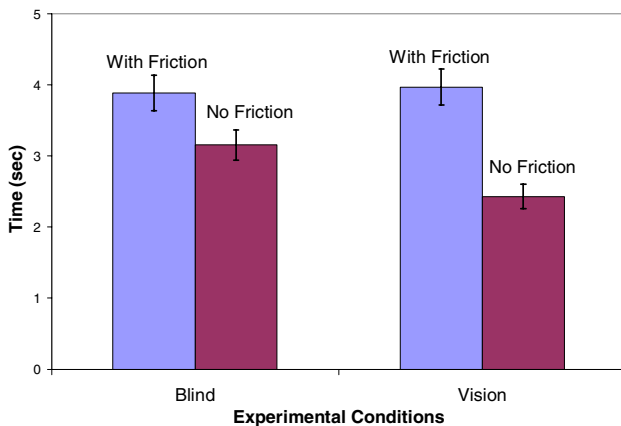


Figure 2. Time spent in contact with tissue samples.

Judgment Errors and Confidence. Mean error rates are presented in Figure 3 for each of the four experimental conditions. There were significant main effects of both vision ($F(1,383)=21.2, p<0.001$) and friction ($F(1,383)=17.2, p<0.001$) on error rate. When subjects operated blind, they made fewer errors in conditions without friction. The error rate was 48% *with* friction and 32% *without* friction. With vision, subjects also made fewer errors in conditions without friction. Here, the error rate was 33% with friction and 9% without friction. Subjects made almost the same number of

errors in the two intermediate conditions: blind without friction, and vision with friction. When comparing the two extreme cases: visual without friction (9%) versus blind with friction (48%), subjects made almost five times more errors. There was no significant interaction between vision and friction.

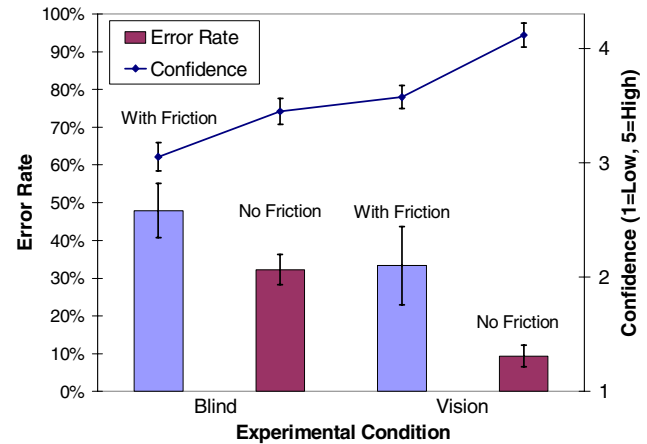


Figure 3. Mean error rate and judgment confidence.

There were significant main effects of both vision ($F(1,383) = 23.9, p<0.001$) and friction ($F(1,383)= 24.0, p<0.001$) on average judgment confidence. When vision was available, subjects reported a higher confidence *without* friction (4.11) than *with* friction (3.57). In the blind condition where confidence was generally lower, subjects also reported a higher confidence *without* friction (mean of 3.45) than *with* friction (3.05) (see Figure 3). There was a high correlation ($r = 0.88$) between correct judgments and confidence.

DISCUSSION

Both of our hypotheses were supported by the results. The presence of friction was responsible for a 45% increase in applied force both when subjects could see and when they were blind. Subjects applied unnecessarily high forces when there was friction in the interface. This finding agrees with the study by Wagner et al in which mean applied force was found to be 50% higher without force feedback when using a robotic surgical tool to dissect simulated tissue.

Friction in the tool/port pair used during testing was measured at 2.2 N, almost equal to the 2.25 N minimum force applied in the vision without friction condition. Following Weber’s Law, this suggests that subjects applied more force in order to perceive and judge contact above the resistance from friction.

We propose that the increased contact time associated with friction conditions was due to inefficient information processing by an inappropriate sensory modality. The 40% higher contact times suggest, as Smyth & Waller (1998) found, that processing of haptic information by the visual system is less efficient.

Results also confirmed the hypothesis that removing friction would decrease the number of errors. If blind and

vision conditions were combined, the error rate doubled when friction was present, rising from 21% to 41%. As with applied force, this follows the same trend as Wagner et al's findings that the loss of haptics increased tissue-damaging errors by a factor of three.

Interestingly, removal of friction actually resulted in a larger improvement to error rate *with vision* than when *blind*, contrary to the other measures. The presence of friction resulted in a 250%, almost three-fold, increase in error rate with vision and a 48% increase when blind. Surgeons generally have the benefit of vision as opposed to working blind. Therefore, the powerful effect of friction, even when vision is available, is a strong benefit.

The removal of friction was associated with a 15% increase in judgment confidence both with and without vision. Being confident in a judgment would be useless if, in fact, one were incorrect in that judgment. Results revealed a high correlation ($r = 0.88$) between confidence and correct judgments. This suggests that the removal of friction, as well as the benefit of vision, can be linked to improvements in both performance and confidence. In other words, when subjects are able to perceive more information, they perform better and are more confident in their tasks.

Every subject claimed to rely heavily on perceived deformation of the sample when vision was allowed. In both friction and friction-free conditions they could see the tool tip deform the sample upon contact. However, they also claimed that vision alone was not capable of providing adequate cues about contact and material properties. Almost all subjects claimed to have not felt anything, even though they visually perceived contact.

CONCLUSION

The major application of this work would be in the design and development of instruments that are capable of eliminating friction in the MIS port. The direction would be to maintain a simple system in which current surgical tools and access ports, including robotic devices, are used in combination with an improved interface device.

The elimination of friction at the interface could 1) make MIS surgery more intuitive, 2) reduce the cognitive processing required to align stimulus-response modalities, 3) improve performance by providing more accurate sensory input, and 4) increase the number and type of open surgeries that can be performed laparoscopically.

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