VISUALLY PERCEIVED FORCE FEEDBACK IN SIMULATED ROBOTIC SURGERY

Cao, C.G.L., Webster, J.L., Perreault, J.O.
Department of Mechanical Engineering, Tufts University School of Engineering

Schwaitzberg, S., Rogers, G.
Department of Surgery, Tufts University School of Medicine

Current robotic systems for minimally invasive surgery do not have effective means of providing haptics to the surgeon. It was hypothesized that providing an analog for force feedback through the visual channel could benefit performance in the absence of actual force feedback. An experiment was conducted to examine performance in a simple line-drawing task in a simulator box using a conventional laparoscopic grasper with inherent force feedback and a robotic manipulator with no force feedback. The task was performed on a hard surface and a soft surface. Physical deformation on the soft surface provided additional visual cues regarding the forces applied during the task. Results showed better performance, in the absence of force feedback, when the visual analog of force was provided. Task completion time was best when physical force feedback was combined with augmented visual feedback. This research has implications for the implementation of haptics in robotic surgical systems.

INTRODUCTION

The motivation for this research grew out of the increasing general interest in robotic applications in minimally invasive surgery. Robotics can enhance surgical performance by increasing dexterity, or automating surgical tasks that are difficult to perform remotely (Garcia-Ruiz, 1998; Ben-Porat, 2000). Robotics can increase the precision and accuracy of the surgeon's fine motor performance by stabilizing tremor, or by scaling down the motions made by a surgeon's hands. There is also the potential to enhance the surgeon's sense of touch through haptic interfaces (Rosen, 1999). It is expected that robotic technology, with its promise of extending human capabilities and enhancing performance, will enable more difficult procedures to be performed. Eventually it could be incorporated into other surgical procedures to make them less invasive, reduce the training time for the next generation of surgeons, reduce surgical errors, and improve patient safety on a global scale.

However, current successful robotics applications in minimally invasive surgery have been limited to two areas: 1) positioning devices for endoscopic cameras and laparoscopic instruments and 2) devices for part-task automation. The promise of robotic surgery is still hindered by challenges in providing tactile and haptic feedback to the surgeon through the robotic interface (Carrozza, Lencioni, Magnani, D'Attanasio, Dario, Pietrabissa, and Trivella, 1997). Even though it has been shown that force feedback can increase speed and accuracy in teleoperation tasks (Salcudean, Ku, & Bell, 1997; Massimo & Sheridan, 1994), implementation of this feedback through a surgical robotic manipulator has proven difficult. Several factors complicate the translation of feedback including electronic noise in the manipulator system and the paucity of available documentation on tissue characteristics. Given these problems, an alternate route for providing force information to the surgeon may be through the visual channel.

The objectives of this study were to determine whether force feedback is crucial to performance in minimally invasive surgery, or if visually perceived force feedback provides adequate information. That is, the ability to perceive pressure via three-dimensional displacement of the working surface may be sufficient in the absence of actual force feedback. It was hypothesized that minimally invasive surgical task performance without force feedback would be inferior to performance with force feedback. It was further hypothesized that visually perceived force feedback would benefit performance in surgical tasks. In order to test the hypotheses, an experiment was conducted to examine both robotic and laparoscopic task performance with and without visually perceivable force information. Two working surfaces, one hard and one soft, were created to mimic the laparoscopic environment in minimally invasive surgery. The soft surface, by virtue of the indentation created by applying a force onto it, would ,in theory, allow the application of force to be visually perceived.

METHODS

Subjects

Six subjects (3 male and 3 female graduate and undergraduate students at Tufts University) participated in this study. Five of the subjects were right-handed and one was left-handed.

Apparatus

Task Space. A *Simulab* endoscopic training box with the dimensions of 39 cm x 39 cm x 10.2 cm was used to simulate the abdominal cavity of a patient. Two different surfaces were created for the task space inside the box: 1) the hard surface was created using a section of a 12.75 cm-diameter PVC pipe (see Figure 1) and covered with a piece of aluminum foil, and 2) the soft surface was created by inserting a layer of soft foam between the PVC and the aluminum foil (see Figure 1). This combination of soft foam and tinfoil was chosen because it prevented any formation of a leading groove which could potentially guide the tool.

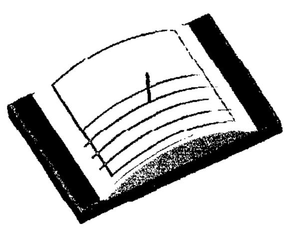

Figure 1a. Horizontal task space

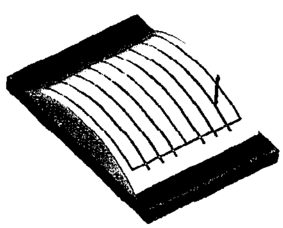

Figure 1b. Vertical task space

Endoscope. A zero degree endoscope was used to obtain a view of the task space in the box. The endoscopic view was projected onto a TV monitor, which was placed in front of the subject at eye-level.

Laparoscopic tool. An *Endo Clinch II* laparoscopic grasper, inserted into the *Simulab* box, was used as the manipulator in half of the test trials in the experiment. The tool grasped a 1.5 mm diameter metal rod with a smoothly rounded tip. The tool also had a ratcheted pistol grip that was kept in the locked position.

Robotic manipulator. The LaproTek Remote Robotic Surgical System (endoVia Medical, Inc.) was used as the manipulator in half of the test trials in this experiment. The robotic system allows the remote manipulation of similar tools in the *Simulab* box, but with no direct force feedback about contact with the task space inside the box. The human operator at the robotic console relies solely on the view of the task space on a monitor.

Task

Subjects were asked to use the laparoscopic tool and the robotic manipulator to draw straight lines on the aluminum foil. In each condition, subjects were allowed to practice for 2 minutes before the test trials. In each trial, they were asked to draw 3 horizontal lines (see Figure 1a) or 3 vertical lines (see Figure 1b) within a specified space (62 mm in length), using their dominant hand. Their goal was to do this as quickly as possible, while keeping the tip of the tool in contact with the surface of the foil at all times for each line. In addition, they were instructed to not push through the aluminum foil when drawing on the soft surface. In order to prevent fatigue effects, the task was designed to last approximately 20 seconds.

Experimental Design

A 2x2 (surface x tool) within-subjects design was used in this experiment. Each of the six subjects performed 6 trials (3 horizontal and 3 vertical in alternate order) in each condition. The orders of surface (hard vs. soft) and tool (laparoscopic vs. robotic) conditions were counterbalanced.

Dependent Measures

Three measures of performance were collected: 1) time to task completion, 2) number of errors, and 3) length of error. Time to task completion was recorded as the time for drawing the three lines in each trial. Timing began when the tool first crossed the boundary of the writing square and ended when the tool exited the boundary after completion of the third line. An error was defined as loss of contact followed by subsequent continuous contact with the foil surface. Length of error was defined as the distance between where the tool left the surface and where it either resumed continuous contact, or crossed the final boundary.

Analyses

Analysis of Variance was performed using an alpha value of 0.05 on the following variables: average time to task completion, number of errors, and length of errors. Only time and number of errors are reported in this paper.

RESULTS & DISCUSSION

Results showed significant main effects in type of surface ($F=6.10$, $df=1$, $p=0.015$) and type of tool used ($F=37.02$, $df=1$, $p<0.001$) for task completion time (see Figure 2). There was no interaction between the two independent variables. In terms of the number of errors made during the trials, there was a significant tool effect only ($F=12.03$, $df=1$, $p<0.001$) (see Figure 3).

As expected, results showed that time to task completion was faster using the laparoscopic tool than with the robot. This confirms that actual force feedback is beneficial to performing the task quickly. Furthermore, task completion time was significantly better when subjects could visually perceive the forces applied by the tools used, regardless of whether or not the subject received actual force feedback (see Figure 2). This suggests that augmented visual information regarding force application is beneficial to task performance when actual force feedback is missing. It also appears to be beneficial to performance even when actual force feedback is available.

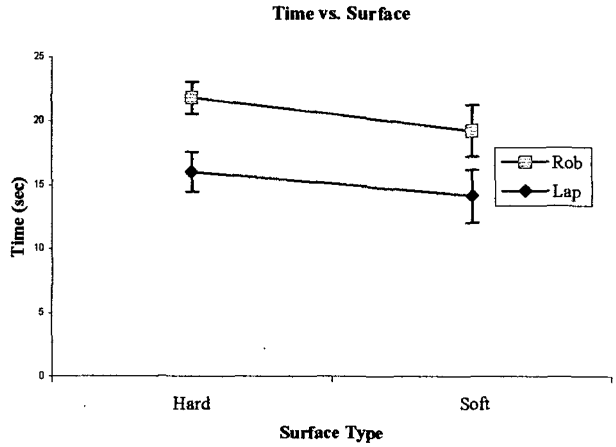

Figure 2. Time vs. surface type.

Contrary to expectation, the number of errors (which reflected the accuracy of force application in tool manipulation) did not decrease when applied forces could be perceived visually (see Figure 3). Similarly, the number of errors recorded for the laparoscopic tool was significantly higher than for the robotic manipulator. This seems to suggest that the direct force feedback obtained through the laparoscopic tool was not helpful in maintaining a fixed amount of force applied to a curved surface. However, another explanation for this unexpected result could be the fulcrum effect produced by the manner in which the tool was inserted into the box. The limited available degrees of freedom (4 DOF) in manipulating the laparoscopic tool may have affected the performance of the line-drawing task, particularly in the vertical direction. The six degrees of freedom of the robotic manipulator might also account for the unexpected consistency in keeping the tool on the working surface throughout the drawing task.

A skipping phenomenon was observed on the hard surface with the laparoscopic tool. In this condition, the tool initially left the surface and then skipped across it several times before the operator was able to maintain continuous contact again. Each skipping sequence was considered one error in the analysis in order to best represent performance.

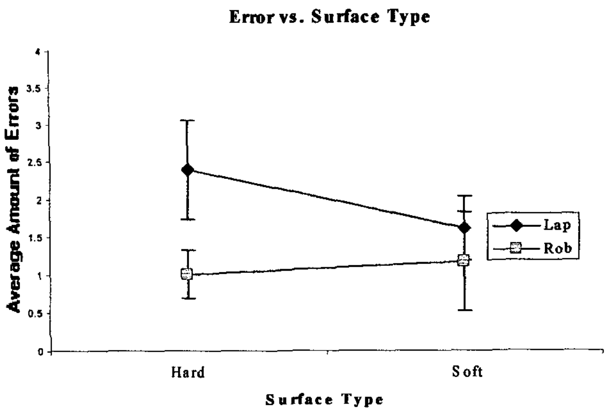

Figure 3. Error vs. surface type.

An ergonomic complication relating to the arm-rest on the robotic console emerged and may account for some of the errors recorded in both hard and soft robotic conditions. Subjects were not allowed to reposition the robotic grippers once the timed task was underway. In a small number of instances, subjects found their hand motions constrained by the arm-rest. Normally, this would have been avoided by using the clutching feature on the robot controller to reposition the handles.

Due to the nature of soft surfaces, a type of error occurred in this condition that was not possible on hard surfaces. Whereas the only observable error possible in the hard surface condition was when the pen broke contact with the surface (not enough force applied into the work surface), it was also possible to push too hard and actually puncture the soft surface. In the latter case, the tool penetrated the aluminum foil and made a hole in the surface. In order to avoid experimental bias favoring hard surfaces, these punctures were not counted as errors, and thus were not included in the analysis. However, even with these errors included, there was no significant difference in the performance. Naturally, no penetration errors were found in the hard surface condition. This observation offers an additional dimension in which one could interpret the results of the experiment and extend the research in the future.

CONCLUSION

The results of this experiment have practical implications for the implementation of haptics into robotic systems for minimally invasive surgery. It is clear that force feedback is beneficial for the performance of a teleoperation task. However, in the absence of force feedback, force analogs provided through the visual channel can also benefit performance. Task completion time is shorter when force information is available, either haptically or visually. Ideally, visual feedback would augment actual force feedback to reinforce the information regarding the remote environment for the surgeon. It is not clear how force feedback affects errors in judging force application in robotic surgery. Results from this experiment would seem to confirm the benefit of robotic systems over laparoscopic tools in removing the physical restrictions on manipulation.

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