Real-Time Haptic Feedback in Laparoscopic Tools for Use in Gastro-Intestinal Surgery*

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Abstract. One of the limitations of current surgical robots used in surgery is the lack of haptic feedback. While current surgical robots improve surgeon dexterity, decrease tremor, and improve visualization, they lack the necessary fidelity to help a surgeon characterize tissue properties for improving diagnostic capabilities. Our work focuses on the development of tools and software that will allow haptic feedback to be integrated in a robot-assisted gastrointestinal surgical procedure. In this paper, we have developed several tissue samples in our laboratory with varying hardness to replicate real-tissues palpated by a surgeon in gastro-intestinal procedures. Using this tissue, we have developed a novel setup whereby the tactile feedback from the laparoscopic tool is displayed on the PHANToM haptic interface device in real-time. This is used for tissue characterization and classification. Several experiments were performed with different users and they were asked to identify the tissues. The results demonstrate the feasibility of our approach.

1 Introduction

Surgeons rely primarily on their senses for the diagnosis and treatment of multiple surgical pathologies. Special attention has been paid to the development of their visual and tactile perceptive abilites through surgical training. Surgeons have traditionally used palpation as the primary feedback for determining whether a tissue is normal or abnormal [1]. The development of minimally invasive surgery has led to a better patient outcome at the expense of these visual and tactile faculties. Through small incisions in the abdominal wall, the surgeon introduces long instruments and camera to perform complicated abdominal procedures. The normal three-dimensional vision becomes two-dimensional and the only advantages are that the new cameras allow the surgeon to have a better visualization of the operative field through increased magnification. Due to

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monocular vision feedback rendered on a two dimensional display, depth perception is lost and a surgeon adapts to this image over time. Haptic feedback is almost completely lost and in most cases limited to gross information. The learning curve becomes a prolonged process of adjustment to these conditions. While this has become an area of increasing interest, some preliminary laparoscopic forceps with force feedback have been tested with good results [2,3].

The real role of haptic feedback in minimally invasive surgery and robotically assisted surgery has yet to be determined. Research seems to suggest that the introduction of haptic feedback can add substantial benefits to robotic systems and facilitate tissue recognition but there are still several hurdles to be resolved such as achieving at least half as much palpation capability through a robotic device [4,5,6,7]. Interaction with the laparoscopic tool remotely in a telesurgical framework poses additional challenges such as sufficiently high network bandwidth and latency issues in communicating over the network [8,9,10,11,12]. Several studies have been done in evaluating the ease of laparoscopic tools through remote manipulation. These studies (though limited to knot tying and suturing) have demonstrated that instrument based mapping gives a more realistic feel of the operative site compared to screen based mapping [13].

The primary goal of this paper is to provide a surgeon with haptic feedback through the PHANToM, a haptic feedback device (manufactured by Sensable Technologies, Inc.) for carrying out robotically-assisted, minimally invasive surgery. One of the chief applications of this research will be the localization of gastrointestinal polyps within the bowel lumen, a task almost impossible to perform with current laparoscopic and robotic devices. It will also enhance the resection of solid organs, allowing the surgeon to differentiate between tumor and normal tissue and between normal and abnormal lymph nodes. Even simple tasks like knot-suture tying can be improved by adding tactile feedback, especially with small sutures.

2 System Description

We have developed an interface to allow the surgeon to manipulate and characterize different tissue samples using the haptic feedback device. We have incorporated tactile sensing capability on conventional laparoscopic tools used in minimally invasive surgery without affecting the ergonomics of the current tool design. This is particularly important since we do not want the surgeon to get used to newer tools than what they currently use. Figure 1 shows the schematic of the overall system that we envision building. Currently, we are interested in solving the force feedback problem through the PHANToM and tool loop.

Our experimental testbed consists of a force sensing laparoscopic tool designed in our laboratory, a PHANToM haptic interface device (manufactured by Sensable Technologies, Inc.), DSpace DS1103 controller board, and tissue samples that we have developed in the laboratory of varying mechanical properties to simulate tissue palpated by a surgeon in gastrointestinal procedures. The experimental test-bed allows us to examine different tissue samples using the

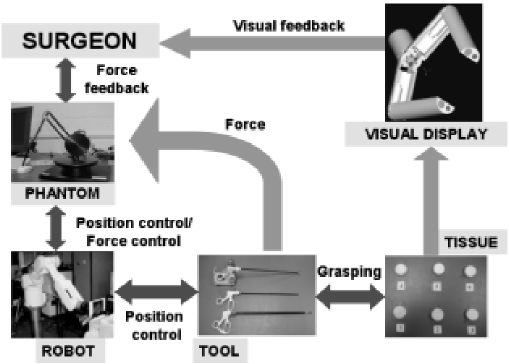

Fig. 1. Block diagram of the tissue characterization using haptic feedback.

force sensing forceps. The forceps are currently manipulated by the surgeon, but our eventual goal is to mount this on the robot arm and control the movement through the PHANToM. The force obtained by the forceps is displayed by the haptic interface device. In our setup, a user grasps the tool on one hand and closes the grasper (analogous to an automated laparoscopic grasper) while the surgeon interacts with the Phantom and feels the grasping force. Real-time force information is measured through appropriate calibration of the strain gages and recording of the signals by the DS1103 controller board.

3 Modeling

We have created our initial prototypes of the force sensing tool using disposable laparoscopic tools for minimally invasive surgery (manufactured by Ethicon, Inc). A laparoscopic grasper, scissor and dissector were modified for testing purposes by attaching strain gages. While these modifications to the tools created sensing capabilities that previously didn't exist, the overall functionality of the tools was preserved as used in practice. The standard laparoscopic tool consists of a 38 cm rod with a jaw mechanism at one end and a handle in the other end. Through an internal pole, the handle controls the opening and the closing of the jaws. These instruments are used to grasp, mobilize and cut the different tissues within the body. Two precision strain gages, manufactured by Measurements group, Inc, were attached to each side of the active handle of the instrument, opposite to each other, using a Wheatstone bridge configuration (see Figure 2). This allows for a deformation measurement of the instrument handle in response to the force applied, therefore producing force feedback correlating to a selected sample of tissue. A position sensor, manufactured by Midori Precision Co, Ltd, was attached to the pivot of the active handle (Figure 3) allowing accurate recording of the angular rotation of the handle. This further establishes a correlation between the deformation of the tissue and the exerted force. In order to increase sensing resolution, the sensors were connected to a transducer amplifier.

Fig. 2. Strain gage attached to the laparoscopic grasper handle.

Fig. 3. Position sensor attached to the laparoscopic tool.

Fig. 4. Calibration setup for the strain gages on the force sensing forceps.

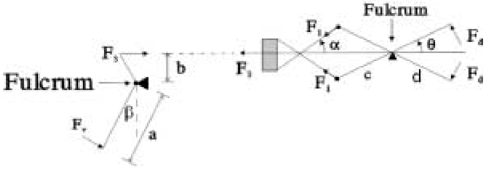

Fig. 5. Force diagram for analysis of the grasping force in relation to the exerted force on the laparoscopic tool.

Calibrating the strain gage and position sensor: In order to obtain valid results, a precise method of measuring the force applied to the active handle is required. For this, a mechanical setup for the laparoscopic tools was necessary. The setup was designed to securely hold the tool in place while incorporating a controlled motion to operate the handle. The force calibration for the laparoscopic tool was done by closing the grasper through the handle and placing an obstruction in the jaw of the grasper which was attached to the force sensor. Figure 4 shows the experimental setup for calibrating the strain gages on the laparoscopic tool. The detailed analysis for the calibration process is given below. Figure 5 shows the kinematic description of the laparoscopic grasper.

Based on Figure 5, we conclude that:

$$F_3 = 2F_1 cos\alpha, \qquad F_1 sin(\alpha + \theta)c = F_d d, \qquad F_v a = F_3 b$$

Finally, we get after simplification:

$$F_d = \frac{ac}{2bd}\left(\frac{sin(\alpha+\theta)}{cos\alpha}\right)Kv \tag{3.1}$$

where F_d is the reaction force exerted on the grasper while grasping the tissue, F_1 and F_3 are the forces in the mechanism internal to the laparoscopic tool, and $F_v = Kv$ is the force exerted by the operator on the laparoscopic handle. The calibration process involved finding the value of K assuming a linear relationship of the applied load to the voltage generated by the strain gages. The experimental value of K was 3.9.

In another experiment, we calibrated the position sensor to measure the grasper movement for a given movement of the position sensor. The handle of the grasper was fixed for different positions of the jaws, which included full open, full close, and a few positions in between these extremes. Using the voltage feedback from the position sensor and the measured angle of the jaws with respect to a reference axis, the following relationship was experimentally determined between the angular movement (θ) of the laparoscopic grasper and the angular movement (β) of the handle:

$$\theta = -12.55\beta + 41.70 \tag{3.2}$$

Tissue modeling and characterization: To perform our testing we created several samples of Hydrogel material with varying consistency. The Hydrogel is created using a combination of polyvinyl alcohol (PVA) and polyvinyl pyrrolidone (PVP). A polymer blend of 90% PVA and 10% PVP was created. The solution was caste into cylindrical molds and subjected to subsequent cycles of freezing and thawing to crosslink the polymer blend, therefore increasing the Hydrogel consistency. A total of six cycles were performed and after each cycle a sample was removed. For the purpose of further discussion the samples were labeled from 1 to 6 based on their stiffness, where 1 was the softest and 6 was the hardest.

4 Experiments

We have conducted two experiments for tissue characterization, the first through force measurement while grasping the tissues without any haptic feedback and the second using haptic feedback.

4.1 Experiment 1

The principle objective of the tissue characterization experiment is to determine the property of the different tissues using a laparoscopic tool. For a given load applied through the grasper, we observed different angular movements of the grasper. In other words, for a given angular movement of the grasper, a stiffer tissue required higher force than a softer tissue. In this experiment, six artificial tissues with different stiffnesses were used (see Figure 6).

The sample tissues were numbered 1 through 6 in increasing hardness (see Figure 6). The operator grasped the samples and the DS1103 board records the real-time force and position signal. The sampling time was 0.4 ms. Figure 7 is the tissue characterization graph which shows the correlation between the deformation of the sample and the force exerted on the sample. The softer the tissue, the more degree of deformation with a lesser force; and the harder the

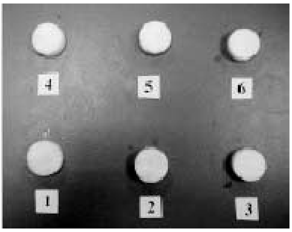

Fig. 6. Tissue Samples.

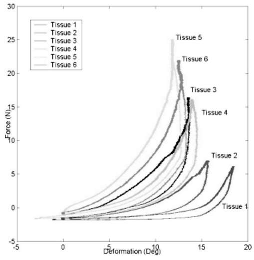

Fig. 7. Force vs. angular displacement plots for various tissue samples.

Fig. 8. Subject interaction with haptic interface.

Fig. 9. Grasping of the tissue samples.

tissue, the less degree of deformation with higher force. This assumption made the Hydrogels a good model to represent simulated tissue samples with different consistency. It is clear from the figure that we were able to obtain quantitative estimate of the force-displacement relationship for the sampled tissues.

4.2 Experiment 2

In the second experiment (see Figures 8 and 9), we displayed the forces exerted on the laparoscopic tool to the PHANToM. The subjects were asked to rank three different Hydrogel samples, from softest to hardest, through pure haptic feedback using the PHANToM. They did not have visual or contact feedback of the different samples outside of the PHANToM. The angular displacement obtained with the laparoscopic tool was kept constant and monitored through the computer screen in order to repeat the same displacement for all the tissue samples. Therefore, as the samples increased in hardness, we can expect an increase in the amount of grasping force necessary to achieve the same angular displacement of the grasper.

The objective of the experiment is to use the PHANToM to differentiate between tissue samples when the displacement of these samples is more or less the same. According to the result of the tissue characterization experiment, we con-

Table 1. Tissue stiffness identification experiment

Subjects	Sample 2	Sample 3	Sample 6
S1	Soft	Hard	Harder
S2	Soft	Hard	Harder
S3	Soft	Hard	Harder
S4	Soft	Harder	Hard
S5	Soft	Hard	Harder
S6	Soft	Hard	Harder
S7	Soft	Hard	Harder
S8	Soft	Harder	Hard
S9	Soft	Hard	Harder
S10	Soft	Hard	Harder

cluded that we can use the laparoscopic tool to get different force/displacement characterization graphs of the 6 groups of tissues. When the displacement of the tissue is the same, the force applied on the tissues should be inversely proportional to the stiffness of the tissue. In this experiment, we chose Hydrogel samples 2, 3, and 6 as reference tissues. Sample 2 was the softest and sample 6 was the hardest. Ten subjects were tested, including several non-surgeons, surgeons and surgical residents with expertise in minimally invasive gastrointestinal surgery. When the subjects performed the experiment, the tissue samples were randomly arrayed and the subject did not know which sample they were testing. They were only in contact with the PHANToM while a second operator performed the grasping of the tissues using the laparoscopic tool. When the operator applied the force on the tissue with the laparoscopic tool, up to a constant angular displacement; the subjects were asked to rank those tissues based on the forces reflected in the PHANToM.

The results of the operator analysis after feeling all three tissues is tabulated in Table 1. As seen from the table, eight out of the ten subjects correctly identified the tissue samples qualitatively in terms of their stiffness. Only two subjects (non-surgeons) were unable to differentiate between samples 3 and 6 even though they were able to differentiate sample 2 as the softest when compared with the other two samples.

5 Discussion

We have developed an apparatus for use in laparoscopic surgery for tissue characterization. In our setup, the operator feels the force in real-time while squeezing the tissue. Our experimental work indicates that even non-surgeons can easily identify the tissue samples being grasped. We performed two experiments, one of which was to record the tissue grasping forces as a function of the angular displacement of the grasper and the other was to identify the stiffness of the tissue sample based on a randomly selected presentation of the samples for the operator to grasp.

We intend to extend this work to automated grasping of the tool through a motorized assembly. The laparoscopic tool would then be attached to the end of the robot arm which would be controlled by the PHANToM. One of the chief applications of this work would be provide haptic feedback to the surgeon in gastrointestinal surgery. By adding haptic feedback to robotic systems, the surgeon should be able to characterize tissue as normal or abnormal and titrate his dissection in order to spare normal tissue while completely removing the abnormal one. The best example is the removal of solid organ tumors, particularly liver tumors, where the surgeons use tactile feedback and intraoperative imaging to localize these tumors and perform an adequate resection with adequate margin. We will create liver models using different stiffness hydrogels in order to simulate liver tumors and perform surgical resection using the laparoscopic tools with force feedback using a robotic arm controlled by the surgeon using the PHANToM device. Our aim is to resect the tumor without disrupting the tumor surface while at the same time preserving the normal tissue.

While this paper addresses the first steps in this direction, there are several issues that need to be resolved. This includes the incorporation of visual feedback of the operative site with haptics and how it relates to operator performance. Also, an understanding of better tactile sensors for achieving palpation in real-time for exploratory tasks over an organ surface as is performed by a surgeon would be helpful. The results presented in this paper represent an important first step in that direction.

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