

Measuring Grasping and Cutting Forces for Reality-Based Haptic Modeling

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Abstract. The modeling of grasping and cutting in surgery are two fundamental tasks that must be achieved for the development of a reality-based haptic interface in robot-assisted surgery. Currently, the lack of these models with soft tissue has limited the accuracy of such interfaces in surgery. As a result, we have taken the first steps in realizing soft tissue models through the development of an automated laparoscopic grasper and tissue cutting equipment to characterize grasping and cutting tasks in minimally invasive surgery. The grasper is capable of generating force feedback that can be felt through a haptic interface device thereby allowing a user to feel the stiffness of the tissue that is being grasped. The cutting equipment employs a surgical scalpel attached to a six-axis force/torque sensor to measure the forces during cutting. The scalpel follows a linear motion created by a DC motor and leadscrew assembly.

Keywords: *Minimally invasive surgery, Surgical Simulation, Robot-Assisted Surgery.*

1 Introduction

Cutting and grasping of tissues are some of the fundamental tasks that are present in any surgical procedure. During open surgical procedures, the surgeon is in direct control of the surgical tools and often relies on his tactile abilities to characterize tissue as normal or abnormal through haptic feedback [1]. With the advent of minimally invasive surgery (MIS), the surgeon loses tactile perception capability as they manipulate tissues and organs with long instruments. Therefore, it is important to design equipment for measuring the grasping and cutting forces in surgery and develop models based on the observed experimental data. Providing reality-based haptic feedback will improve the surgeon's diagnostic capabilities and thus lead to better patient care, reduced trauma, and lower healthcare costs.

In the area of grasping, researchers have proposed many solutions for incorporating haptic feedback into laparoscopic tools through the addition of force and position sensors [2-4]. Additional work in this area has also led to the creation of new laparoscopic tools with force feedback capabilities [5, 6]. Modeling tissue cutting has been explored to a limited extent by researchers and therefore no standard methodology for realistic simulation of the cutting process currently exists. Most of the research does not take into account the physics behind cutting (such as energy exchange) or are not reality-based systems [7-10].

Therefore, the development of these reality-based haptic interfaces must start with the tissue/tool interactions that occur. Once these interactions can be accurately determined, a realistic model and subsequent haptic interface can then be developed.

2 Materials and methods

Based on the above motivation, we have designed and developed a laparoscopic tool capable of providing force feedback to the surgeon through a haptic interface device and a cutting apparatus for measuring the cutting forces. This section is divided into two parts: a) design and development of a laparoscopic grasper with force feedback, and b) design and development of the tissue cutting equipment.

2.1 Design and development of a laparoscopic grasper with force feedback

Our laparoscopic tool prototype employs a cable-driven system for actuating the two jaws of the laparoscopic grasper. For the design of this prototype, we restricted the outer diameter of the tube to 15mm to conform to conventionally used laparoscopic tools. Additionally, our automated grasper has 90 degrees as the range of jaw motion. Since our prototype is cable driven, we designed the pulley on the end of the grasper such that we get an effective transmission ratio of 1:2.7, i.e., for every degree of movement on the motor side we get 2.7 degrees of jaw motion. Our prototype of the laparoscopic tool employs a cable-driven pulley system actuated by a DC motor with an incremental encoder attached to its shaft (See Figure 1). Since the motor is direct drive without any gearing, the movement recorded by the encoder represented the true motion of the motor shaft. This allows for accurate positioning and control of the jaws. The entire assembly, comprised of the laparoscopic tool and motor, is mounted on an aluminum plate that can be attached to the end-effector of a robot arm. The cable-drive system consists of two steel cables that transmit the torque from the motor to the jaws. A pulley mounted to the motor shaft with grooves for placing the end crimps of the cable combined with a moving vertical guide for the cables allows for tensioning the cable mechanism without much effort. On the tool-tip end, the cable wraps around a second pulley and travels back to the motor pulley where the other end is secured. The cable routing for the second cable is the same with the exception at the end effector where it travels in the opposite direction compared to the first cable. This allows for opposite motion of the jaws (to enable closing and opening the jaws) by using only one motor (actuator) instead of two and also enables equal precise movement of each jaw in the opposite direction.

The entire mechanism is controlled via a PC using the dSPACE DS1103 controller board (manufactured by dSPACE, GmbH) and a proportional + derivative (PD) feedback control law. Based on the error in the commanded and actual position, the motor current opens/closes the jaws resulting in controlled force exertion between the jaws. The grasping force at the jaws is calibrated with the motor current, which is presented in the results section.

2.2 Design and development of the liver tissue cutting equipment

The design of our liver tissue cutting equipment consists of a scalpel-blade cutting subsystem, a computer control subsystem, a digital data-acquisition subsystem, and a data

Figure 1.

post-processing subsystem. The test equipment to measure the liver cutting forces was designed to have multiple capabilities such as: a) varying the angle of cutting the liver, b) adjust the height of the scalpel by moving the cutting mechanism over a vertical column to control the depth of cut, and c) variable cutting speed (to measure the effect of cutting speed on cutting forces and strain rates within the specimen). The entire cutting mechanism consists of two vertical supports that can be adjusted in the range of 1 to 2 feet from the base, a lead screw assembly with a geared DC motor and an incremental encoder (manufactured by Maxon Motors), and a JR3 precision 6 axis force/torque sensor (model 85M35A-I40) to which a surgeon's scalpel is attached (See Figure 2). We used the number 10 Bard-Parker stainless steel surgical blade in our experimental studies. The cutting blade traverses linearly based on the rotary motion of the DC motor. An anti-backlash nut connects the lead screw to the force sensor. The scalpel is screwed to the force sensor and the force sensor is mounted on an aluminum plate with one end attached to the anti-backlash nut traveling along the lead screw and the other end on a lower guiding shaft (parallel to the lead screw) with a linear bearing to provide low friction linear travel. The entire assembly has been designed to provide 8 inches of travel distance for cutting the liver specimen. The dSPACE DS1103 controller board (manufactured by dSPACE, Inc.) records the position and force data from the motor's encoder and force sensor in real-time. We have implemented a position + derivative (PD) controller to enable precise movement of the motor (and hence the cutting blade during cutting tasks).

The liver was obtained from freshly slaughtered pigs and transported to the lab within 2 hours post mortem. During the experimental setup, the liver is placed on a bed of saline soaked gauze, sprayed with saline and sealed in a container. The saline solution is prepared at room temperature. The tissue sample is not preconditioned because in surgery the cutting forces experienced by the surgeon are on non-preconditioned tissues. Before starting the experiment, the sample is cut into pieces of size of 3x4x1 inches and placed on sand paper to eliminate slip. The outer rim of the sample is covered with petroleum jelly to minimize moisture loss during the experiment. A bar of rectangular shape made of machineable plastic with an array of small nails clamps at the top end of the liver to simulate a single constrained boundary surface. While this is not an exact replication of the boundary conditions for a human liver (which is partially attached to the diaphragm) this is none-the-less a valid simplification for our initial tests and model.

3 Results

3.1 Laparoscopic grasper calibration and evaluation

Calibration of tool: Our first experiment was to calibrate the force exerted by each jaw with respect to the motor current. Since our tool does not use any external force sensors, we must develop the relationship between the motor current and force output at the jaw using a JR3 precision force/torque sensor (model 85M35A-I40). We positioned the force sensor against one jaw of our grasper and slowly increased the motor current. This causes the jaw to apply a force against the sensor proportional to the motor current (there is no slip in the cable). The

Figure 2.

results of this experiment have shown a linear relationship between the force exerted at the jaw and motor current. Using this calibration technique we can accurately estimate the grasping and cutting forces of tissues in real-time.

Friction estimation and compensation: To provide a seamless grasping and cutting action at the tool tip, it is necessary to estimate and feed-forward the friction torque in our controller model. The importance in doing this is to achieve transparency in the interface. As described above, our laparoscopic tool uses the current applied to the motor to calculate the grasping force. Therefore, if there wasn't compensation for the friction in the system, the user would feel a combination of the grasping forces and frictional forces, which could lead to error in identifying different tissue samples. To estimate the friction torque, we opened and closed the jaws at a very low velocity (0.77 degrees/sec) and recorded the voltage applied to the motor. By moving the motor at such low velocities, we can assume that the torque required to cause the movement is the friction torque in the mechanism. We observed that the friction torque is not a constant across the range of jaw motion. Additionally, we observed a directional dependence of the friction torque in our prototype (i.e., friction torque profile while opening the jaws was higher than that while closing them). However, the maximum friction in either direction had the same magnitude of 0.045 Nm.

Evaluation of grasper through characterization of tissue samples: In the final experiment, we grasped artificial tissues, made up of hydrogels, of varying hardness and performed experiments to characterize them using force feedback from our laparoscopic tool. We chose three artificial tissue samples in our tissue characterization experiment. For sample 1 (softest), a 1.4N force was required for grasping to a 30-degree angle between the jaws. Samples 2 (medium) and 3 (hard) required 2.2N and 2.8N grasping force respectively for the same deformation. Therefore, the three tissues can be easily distinguished based on the force feedback from the grasper. Additionally, three tests were performed on each sample to determine if the force vs. position data was repeatable. All three tests showed very similar results with very little error. Therefore, the validity of our tissue characterization experiment was proved and we can use this device to “feel” the grasping forces of various tissues.

3.2 Liver Cutting Experiment

We were interested in obtaining the force vs. displacement characteristics while cutting pig liver. In our experiments, the cutting blade was set to move at constant velocity of 0.04 inch/second with a travel distance of 5 inches. The x, y, and z components of the cutting forces were measured by the JR3 force sensor and were plotted versus the displacement of the cutting blade (See Figure 3). Our experimental data revealed that the cutting path was formed by a repeating sequence of localized deformation followed by localized micro fracture (onset of localized crack growth). The measured force versus cut-length (displacement of the cutting blade) curves are repeatable in the way that it starts from a small force during tissue deformation and increases to a higher force as impending localized fracture is about to take place, then the force suddenly drops as onset of localized crack extension occurs. Each visually observed localized blade cut on the tissue clearly corresponds to a sudden drop of the force measured by the force sensor. A filtering procedure

Figure 3.

was developed to post-process the data to produce a banded curve of force versus cut-length to illustrate the “hilltops” and “valleys” of the sequence of localized loading and unloading in the tissue specimen during cutting. It was observed that the magnitude of the force directly correlated to the depth of cut.

4 Discussion

We have developed a laparoscopic grasper with force feedback capability and a tissue cutting apparatus capable of measuring the cutting forces. Experimental work has shown that the laparoscopic grasper has low friction and can accurately measure grasping forces. The results have also shown that tissue samples of varying hardness can be easily characterized. The tissue cutting equipment has shown its ability to measure the intrinsic cutting forces versus the cut-length of a tissue specimen. Results from parametric experiments reveal that the cutting process consists of a sequence of intermittent localized fracture (localized crack extension in the tissue). In our future work, we are interested in understanding the effect of depth of cut, speed of cutting, and tissue boundary constraints on the variation of the cutting forces. These results will aid in developing the foundation of a reality-based haptic interface for cutting and grasping tasks in robot-assisted surgery.

5 Acknowledgements

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Figure Captions

Figure 1: Laparoscopic grasper with force feedback

Figure 2: Tissue cutting equipment

Figure 3: Force data from liver sample

Figure 1

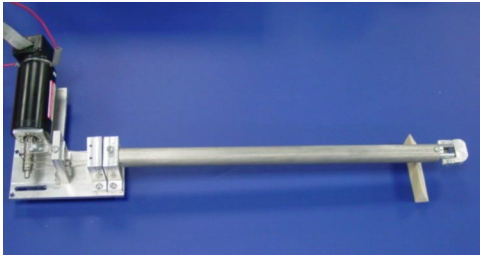


Figure 2

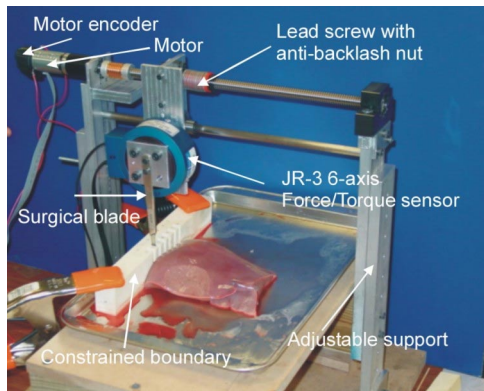


Figure 3

