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Measuring In Vivo Animal Soft Tissue Properties for Haptic Modeling in Surgical Simulation

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Abstract. To provide data for the design of virtual environments and teleoperated systems for surgery, it is necessary to measure tissue properties under both in vivo and ex vivo conditions. The former provides information about tissue behavior in its physiological state, while the latter can provide better control over experimental conditions. We have developed devices to measure tissue properties under extension and indentation, as well as to record instrument-tissue interaction forces. We are creating a web database of data recorded from porcine abdominal tissues.

1. Introduction

To produce realistic behavior in virtual environment simulations for surgical training, it is important to have good models of tissue behavior and instrument-tissue interaction. Although much of the research in modeling the mechanical behavior of tissue has emphasized load-bearing tissues for biomechanics, there has been work on measuring and modeling the behavior of soft tissues as well [1,2]. This work has relied on ex vivo tissue samples from animals and human cadavers. More recently, devices were developed to test tissue behavior in vivo under limited conditions [3–5]. Several devices have also been created to measure interaction forces between instruments and tissue [6,7].

Each of these types of measurements has advantages and limitations. Ex vivo tissue allows precise control of sample shape for modeling. In vivo measurements give data on tissue in its natural state (i.e., perfused with blood, in a typical stress state, and with muscle activation). Mounting surgical instruments with force sensors can measure interaction forces that are too complex to model, but direct tissue measurements are necessary to augment this data. Our research group has developed devices for each of these types of measurements, allowing us to produce a database of properties and integrate models based on data from different types of measurements.

2. Methods

2.1 Tissue Extension

To measure in vivo and ex vivo properties of tissues in extension we designed a device with interchangeable jaws to grasp tissue (Figure 1). A stepper motor-driven linear stage

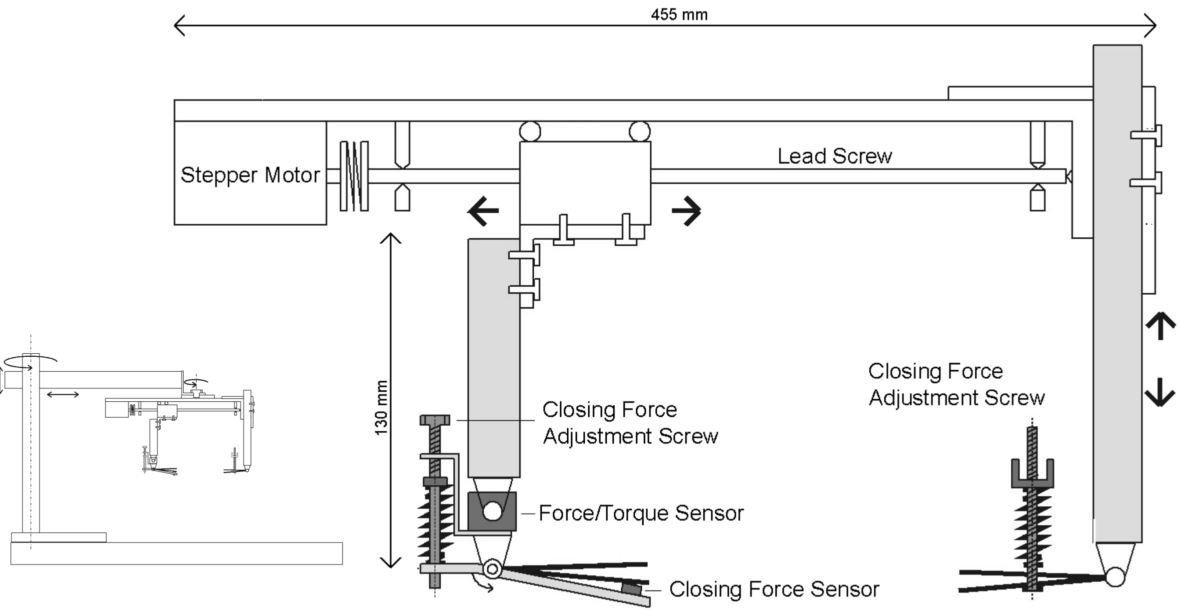

Figure 1. The instrument used for unixial stretching experiments in-vivo and ex-vivo. Inset shows how the device mounts on the operating table.

allows one of the jaws to be moved with specified velocity and acceleration until a certain position or force is reached. The closing force of this jaw is recorded by a button force sensor. The forces that the tissue exerts on the jaws are recorded by a 6-axis force-torque sensor. The jaws can be rotated to grip the tissue at an angle. Dimensions of the device are such that it can be used in the abdomen of a pig. The device can be mounted on an operating table.

The button sensor that measures the closing force is a miniature load cell (Sensotec model 13, www.sensotec.com). This sensor is read by a 12 bit A/D converter. The 6-axis force-torque sensor is a nano-17 transducer from ATI Industrial Automation (www.ati-ia.com) with a resolution of 0.0125 N. Custom software on a PC records the force/torque data from the two sensors, the position from the stepper motor, and the time with a frequency of 40 Hz.

For the in vivo measurements, jaws from laparoscopic Babcock graspers (U.S. Surgical, www.ussurg.com) are placed on both sides on the instrument. The distance between the jaws is marked on the tissue before clamping the tissue in the instrument. Soft tissues have very low resistance to deformation in their physiological rest state and even careful handling of the tissue can cause it to deform and change the perceived initial length. The viscoelastic behavior of the tissues requires all measurements to be performed on a new stretch of tissue.

Different organs required different techniques. For example, the small intestine was grasped as a double layer of tissue. The stomach was emptied and incisions were made in the stomach wall to insert the grasper jaws to grasp a single wall. Measurements on the intestine and stomach were carried out in both longitudinal and transverse directions. The gall bladder was first drained and than removed from the liver to avoid the mechanical properties of the liver interfering with the measurement.

For ex vivo measurements, custom clamps are used that minimize local stress concentrations. Ex vivo data is often presented on tissues in the preconditioned state. This state is reached by stretching and relaxing the tissue until the obtained stress-strain loop no longer changes over each cycle. Preconditioning of tissue makes it easier to compare results because repeatable measurements can be obtained. Since information about the original state of the tissue is lost in this process, we also obtain first-stretch measurements of the tissues. To minimize the change of properties during removal of the tissue, the time between removal and measurement needs to be kept as short as possible. To minimize stretching of tissue in the plane of measurement while preparing the samples, the samples were cut with a 'cookie cutter' that only exerted vertical forces while cutting. To trace the change in geometry of the tissue while being cut out of the organ and cut into a sample, the tissue was marked at certain points before removal and compared to the distances between the marks afterward. For the measurements on the stomach, the mucosa was detached from the muscularis and serosa.

For analysis, the data can be curve-fitted to the function $F(\lambda) = \alpha e^{\beta\lambda}$ in which λ is the Lagrangian stretch ratio l/l_0 and F is the measured force [8]. Taking the derivative $dF/d\lambda = \beta F$ results in parameter β as a measure of the stiffness of the tissue.

2.2 Tissue Indentation

Some tissues are too fragile to be tested under tension. For these, a system was designed for indenting abdominal tissues in vivo. The system consisted of a position- and velocity-sensitive indentation device and a force sensor mounted at the end of the device. The indentor used was a Phantom 1.5 haptic device from Sensable Technologies (www.sensable.com) while the force sensor was a six-axis force/torque sensor (described in section 2.1). The nominal position resolution of the Phantom was 30 microns. The sensor was mounted between the Phantom and a 2 cm diameter hemispherical plastic indentor. Computer control was provided by a Silicon Graphics workstation, which sampled position and force at a rate of 30 Hz. The Phantom can be used in a controlled mode so that indentation occurs at a constant velocity to determine viscoelastic effects, or contact force increased up to a set level.

A platform rigidly attached to the Phantom was arranged to lie over the abdominal cavity so that tissues could be pulled out of the abdominal cavity and placed on the platform. The sample tissues were not separated from their anatomical connections ensuring that the tissue properties were gathered in a physiological state. After a tissue was placed on the platform, the Phantom indentor and ATI sensor were used to measure displacement and contact force information. So far, we have gathered data for porcine stomach, liver, spleen, and skin.

2.3 Instrument-Tissue Interaction Forces

The third set of measurement devices were designed to record interaction forces between instruments and tissue. Force and torque data was collected while driving a needle through a variety of tissue types while applying tension to the tissue. A standard laparoscopic grasper with a 5 mm diameter shaft was modified to incorporate a force-torque sensor in the shaft (Figure 2, top). The shaft was cut approximately 5.5 cm from the handle and 4 cm from the grasper tip. Two aluminum mounting fixtures consisting of a tube fitted to the shaft and an end plate for attachment to the mounting plates of the sensor were used. The cylinder was attached to the instrument shaft with set screws while the end plate was attached with fasteners to the sensor mounting surfaces. The inside diameter of the fixture on the grasper side was drafted to allow the jaws to be opened, while two additional set screws were used to clamp the jaws. The sensor used was the six-axis ATI sensor described in section 2.1. A curved tapered needle was clamped into the jaws such that the plane of curvature was normal to the instrument shaft. The tip of the needle was offset

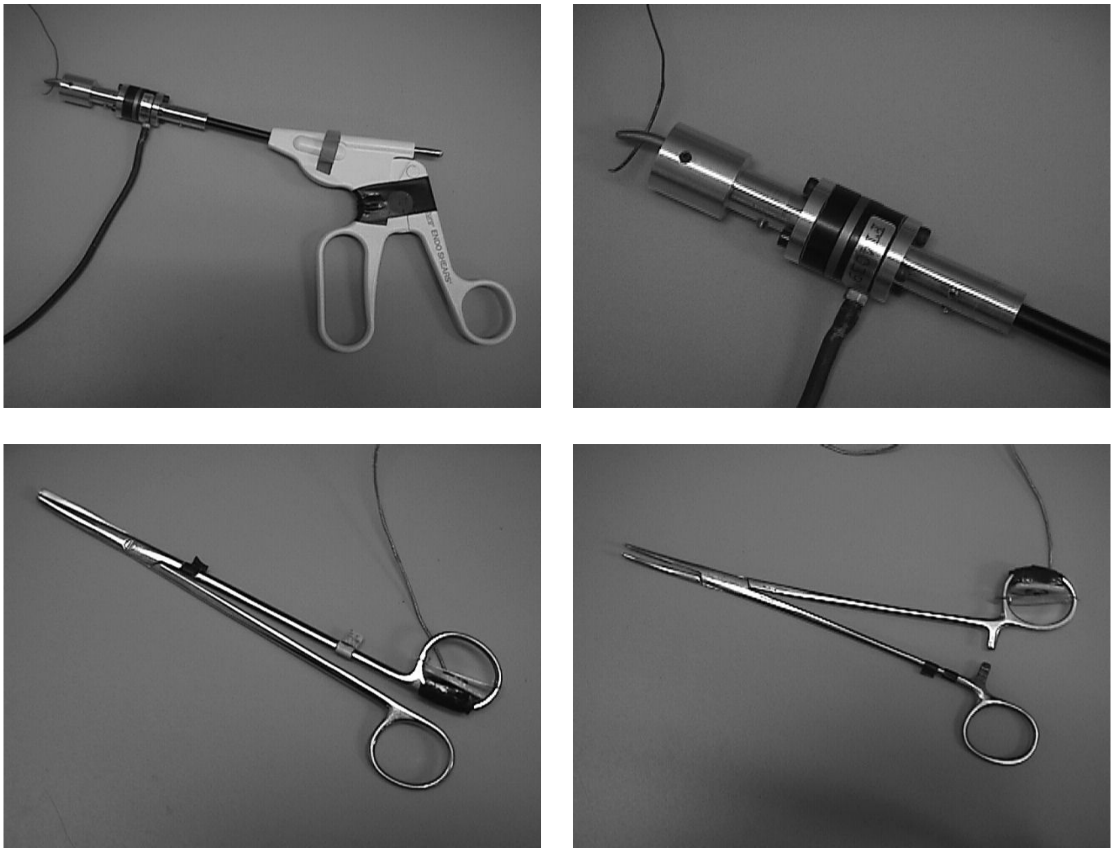

Figure 2. Force sensors mounted on surgical instruments. Top: 6-axis force/torque sensor on adapted grasper (left); close-up of sensor attachment (right). Bottom: load cell mounted on scissors (left) and clamp (right) to measure cutting and spreading forces, respectively.

from the sensor origin by 10 mm along the x-axis, 8 mm along the y axis, and 42.7 mm along the z axis. Force data was recorded at a rate of about 30 Hz.

In the needle-driving task, the needle was driven through a bite of the tissue, as in suturing, while an uninstrumented grasper was used in the opposite hand to put the tissue in tension. The 'traction' task measured the amount of force on the instrument being used to apply the tension. The needle was first driven through the tissue as a means of holding the tissue, then the appropriate amount of tension was applied. All of the tasks were performed by a surgical resident, whose judgment determined the size of the bite of tissue used and the amount of tension necessary for putting in a suture. For each task and tissue combination, five sets of data were collected. A continuous stream of data was collected during the performance of the task. Trials were performed on both a 20 kg pig and an immature 10 kg pig. There were eight tissue and activity combinations: driving a 3.0 suture through anterior stomach wall tissue, driving a 3.0 suture through the abdominal wall, putting the anterior stomach wall in tension, driving a 3.0 suture through bladder, putting the bladder in tension, driving a 3.0 suture through the esophagus tissue, driving a 4.0 suture through small intestine tissue, and driving a 4.0 suture through the common bile duct.

The second set of data was collected using a 1-axis force sensor to measure the forces involved in cutting and spreading tissue. The one axis sensor was mounted on the handle of standard open surgical instruments used for cutting and spreading tissues (Figure 2, bottom). The instruments used were curved Metzenbaum scissors and a curved Kelly clamp. A fixture was built such that the forces applied between the surgeon's thumb and the handle were collected. Five tissue and task combinations were investigated using the immature pig: dissecting peritoneum near the common bile duct, spreading mesentery,

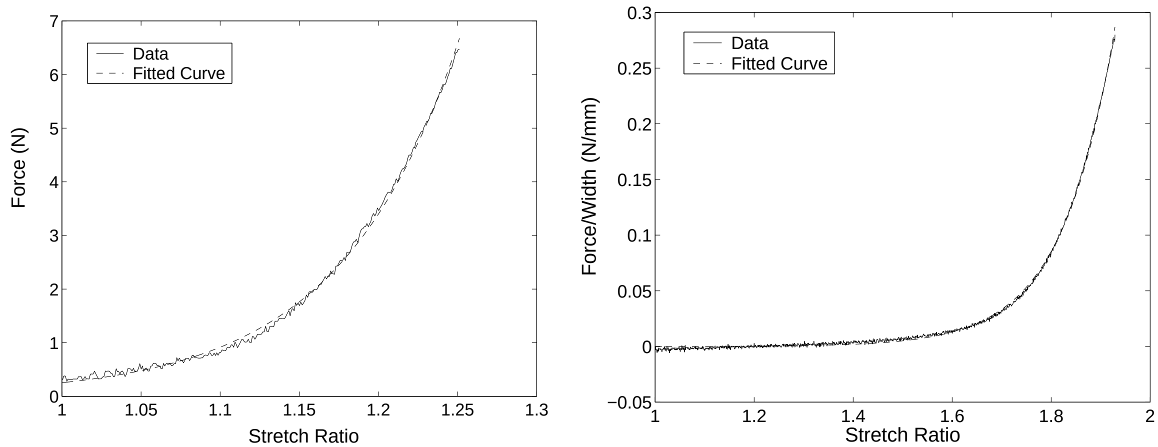

Figure 3. Plots of in-vivo (left) and ex-vivo (right) measurements of porcine small intestine. The width of the ex-vivo sample is 15mm. The in-vivo measurement is performed with an 8mm wide babcock gripper.

cutting anterior stomach wall, cutting abdominal wall, and cutting skin. Each task was repeated five times.

3. Results

Measurements were obtained in the Experimental Surgery Laboratory at UCSF from pigs used immediately prior to the experiments for other research. The animals were anesthetized and supervised under appropriate animal care protocols. An incision was introduced in the belly to allow access to the abdominal cavity.

Both in-vivo and ex-vivo uniaxial stretching experiments were been performed on porcine abdominal tissue. We have performed measurements on the gallbladder, stomach (muscularis and mucosal layers), and large and small intestine, and achieved excellent exponential fits to obtain curve parameters. Two typical examples of preliminary results with exponential fits are presented in Figure 3.

Curve fitting the datasets to the function $\alpha e^{\beta\lambda}$ gives the following values for α and β:

in-vivo: $\alpha = 4.3\text{E-}7$ $\beta = 13$

ex-vivo: $\alpha = 3.7\text{E-}9$ $\beta = 9.4$

Differences in boundary conditions between the in-vivo measurements and ex vivo measurements cause the curves to have a different shape. The slope of the in vivo curve increases at lower stretch ratios than the ex vivo curve. The effect of preconditioning of ex vivo tissue is shown in Figure 4. With the increase in the number of cycles, the hysteresis decreases while the curve shifts. The differences between the cycles become smaller with increasing number of cycles.

In the instrument-tissue experiments, the data of interest included the maximum forces and torques on the instrument and any differences between the adult and immature pigs. For both the large and small animals, the maximum forces in most trials were between 1.5 and 3 N. There were isolated instances in which forces above this range, between 6 and 12.5 N, were recorded. These cases occurred in situations in which the instrument was being used to lift the weight of the tissue being investigated, so that the force on the instrument was a combination of forces due to the tissue properties and those due to gravity. Over all the trials, the forces and torques in the adult were slightly higher, but not by a significant amount. The maximum forces recorded on a given trial in the cutting and spreading experiments ranged between 3–6 N.

Additional data from these trials and results from the indentation measurements are available on our web page, http://robotics.eecs.berkeley.edu/~tendick/tissue.html.

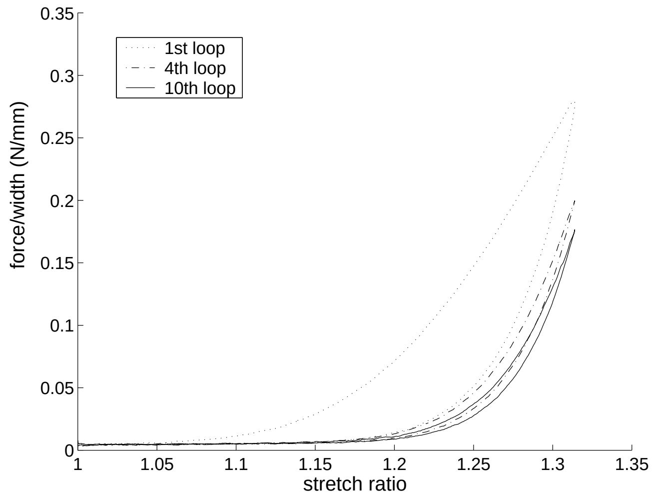

Figure 4. Ex vivo preconditioning of stomach mucosal tissue, showing first, fourth, and tenth stretch-relax cycles of the same tissue sample.

4. Future Work

The project is proceeding in several directions. We are gathering a database of properties that will be made public on the web site as a resource for other researchers. We are attempting to develop finite element models to relate in vivo tissue and instrument-tissue interaction data to the more accurate ex vivo data to estimate the result of tissue behavior local to contact. In particular, we are interested in estimating when tissue damage will occur as a function of instrument type, contact, and tissue type. Finally, we are using the data to establish design parameters for teleoperative surgical systems as well as simulation.

5. Acknowledgments

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