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Measurement of *In-vivo* Force Response of Intra-abdominal Soft Tissues for Surgical Simulation

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Abstract. The lack of data on *in-vivo* material properties of soft tissues has been a significant impediment in the development of virtual reality based surgical simulators that can provide the user with realistic visual and haptic feedback. As a first step towards characterizing the mechanical behavior of organs, this work presents *in-vivo* force response of the liver and lower esophagus of pigs when subjected to ramp and hold, and sinusoidal indentations delivered using a haptic feedback device, Phantom, employed as a mechanical stimulator. The results show that pulse significantly affects the reaction forces and that the lower esophagus is 2 to 2.5 times stiffer than the liver.

1. Introduction

Laparoscopic surgery is being employed for an increasing variety of procedures, spawning a crucial need for tools to train surgeons for surgeries. A surgical simulator is one such tool that involves an immersive virtual environment where the human user interacts with virtual organs using his/her sense of vision and touch. For the virtual environment to be realistic and result in positive training transfer, it is generally expected that physically based models of organs and tissues must be used. Computation of realistic surgical tool-tissue interaction forces and organ deformations requires elucidation of physical laws governing the behavior of soft tissues [1]. To compute these deformations and reaction forces, apart from the consideration of force equilibrium and boundary conditions, *in-vivo* material properties of the soft tissues are required. *Ex-vivo* data [2] is not suitable since the material properties vary considerably from *in-vivo* data due to a variety of factors such as loss of blood pressure and degeneration of tissues.

Determination of *in-vivo* properties of soft tissues is a difficult problem. Efforts have been made to measure *in-vivo* intra-abdominal tissues [3, 4]. Attempts have also been made to

measure *in-vivo* intra-abdominal tissue properties using specially designed instruments [4-6]. However, the measurements made until now are not suitable for our application, because of the limitations on the range, resolution or frequency bandwidth of the measurements as well as the particular organs that were tested. We are interested in the linear as well as the nonlinear response of the soft tissues and their viscoelastic properties under compressive and shear loading. For realistic simulation of laparoscopic procedures we require a systematic study of the mechanical behavior of organs and data suitable for the development of the simulator.

In this paper, we present the *in-vivo* force response of the liver and lower esophagus of pigs subjected to ramp and hold stimuli as well as low frequency vibration stimuli delivered using the Phantom haptic interface device.

In the next section, we briefly describe the setup for the experiment, including the equipment used, the type of stimuli applied and the experimental procedure and in section 3, we present some of our experimental results.

2. Methods

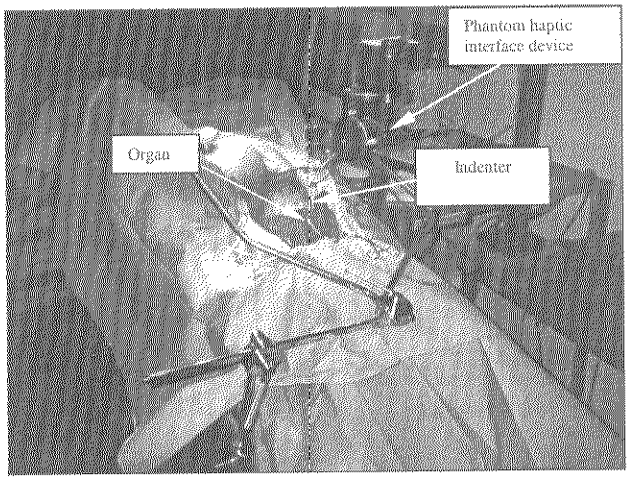

Figure 1: Experimental setup for tissue property measurement.

a) Setup

In-vivo force response of the intra-abdominal organs of pigs was obtained by applying indentation stimuli to the organs and measuring the corresponding reaction forces. The indenter used was a 2mm diameter flat-tipped cylindrical probe. The stimuli were delivered using a force feedback haptic device, Phantom Premium-T 1.0 (SensAble Technologies) that was programmed to perform as a mechanical stimulator. The Phantom has a nominal position resolution of 30μm and a frequency bandwidth that exceeds stimulus frequencies employed here.

A six-axis force sensor from ATI Industrial Automation, Nano 17, was used for measuring the reaction forces. The Nano 17 has a force resolution of 0.781mN along each of the three orthogonal axes when attached to a 16-bit A/D converter. The indenter was fixed to the tip of the Phantom with a force sensor in-between to accurately sense the reaction forces. Using

position control, the Phantom was programmed to indent the organ to different depths at different ramp velocities. Force measurement was sampled at 200Hz using custom software. An 850MHz Pentium III PC was used for both position control and data acquisition.

b) Indentation Stimuli

Indentation stimuli included both ramp and hold in the three orthogonal directions as well as sinusoidal indentations. Ramp and hold indentations explore the force response of the organs to different displacements and the effect of ramp velocities on the response. These indentations reveal the viscoelastic nature as well as non-linear steady state force-displacement relationship of the soft tissues. Indentations up to 8mm from the resting surface of the organs and ramp velocities up to 8mm/s were applied.

Effects of anisotropy may be studied by comparing the force-displacement relationships of the organ in the three orthogonal directions. Ramp and hold indentation stimuli in the normal (Z) direction were applied by ramping the indenter to the prescribed depth in one second. The indenter was then held in place for 20 seconds. Force response was recorded for the entire period. For the indentation stimuli in the other two orthogonal directions, a preindentation of 4 – 6mm was applied to the organ in the Z direction. Table 1 presents the different ramp and hold indentation scenarios that were used.

Displacements (mm)	Ramp Velocity (mm/s)	Direction
1.0	1.0	Z, X, Y
2.0	2.0	Z, X, Y
4.0	4.0	Z, X, Y
6.0	6.0	Z
8.0	8.0	Z

Table I. Ramp and hold indentation conditions applied to the organs.

Sinusoidal indentations reveal the frequency dependency of the organ response. Low frequency sinusoidal indentations (0.5, 1.0, 2.0 and 3 Hz) were applied to the organs in only the Z-direction. The amplitude of the sinusoids was 1.5mm superimposed over a pre-indentation of 4mm. This ensured that the indenter stayed in contact with the organ over the entire course of stimulation.

c) Experimental Procedure

The pig was first put under general anesthesia and placed on the surgical table (see Figure 1). A midline incision was made at its abdominal region and dissection carried out on the anatomical structures to expose the organs. The tip of the Phantom, with the indenter attached, was then lowered into the abdominal region. Preliminary experiments revealed that breathing caused motion and forces that exceeded the stimulus ranges employed here. Only during the stimulus application periods was the respirator turned off and breathing of the pig held, so that the force response of the organ was unaffected by breathing cycles.

3. Results

Force response from indentation stimuli performed on the liver and the lower esophagus of pigs is presented in this section. These indentation stimuli were delivered to three female pigs that weighed about 32kgs to 65kgs. Typical results are presented below.

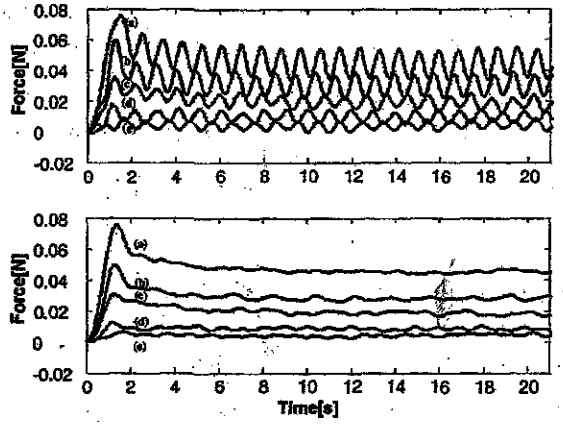

Figure 2. *In-vivo* force response from the liver to ramp and hold stimuli under displacement control. (a) velocity of indentation=8mm/s, depth of indentation=8mm; (b) velocity of indentation=6mm/s, depth of indentation=6mm; (c) velocity of indentation=4mm/s, depth of indentation=4mm; (d) velocity of indentation=2mm/s, depth of indentation=2mm; (e) velocity of indentation=1mm/s, depth of indentation=1mm. Raw data is shown in the top panel and data with the effect of pulse on force response removed is shown in the bottom panel.

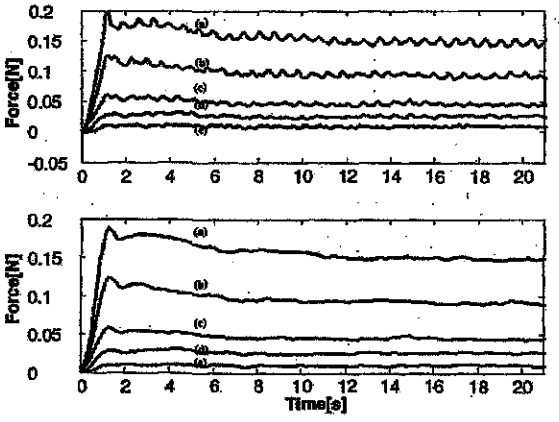

Figure 3. *In-vivo* force response from the lower esophagus to ramp and hold stimuli under displacement control. Same format as Figure 2.

Figures 2 and 3 above show some typical force response as a function of time of the liver and the lower esophagus subjected to ramp and hold indentations in the Z-direction. Various velocities and depths of indentation were delivered as shown in the figures. The approximately

sinusoidal variations in the force response in the upper panels of the figures indicate the forces generated due to the pulse of the pig. These forces are superimposed on the inherent force responses of the organs as the indenter is held in place at the required depth.

To observe the force response of the organs to the ramp and hold indentations without the influence of the pulse, a low pass digital filter was designed with a cutoff frequency just below the frequency of the pulse rate to generate the plots in the lower panels of the figures. These plots show the relaxation behavior of the organs as well as steady state force response. Comparing Figures 2 and 3, we see that the lower esophagus is 2 to 2.5 times stiffer than the liver.

Figure 4 shows the force response from the lower esophagus when subjected to sinusoidal indentation at 1.0Hz. The plot on the left shows the force response from the lower esophagus as a function of time while the plot on the right shows the force response as a function of displacement. The nonzero area of the loop indicates viscous energy dissipation.

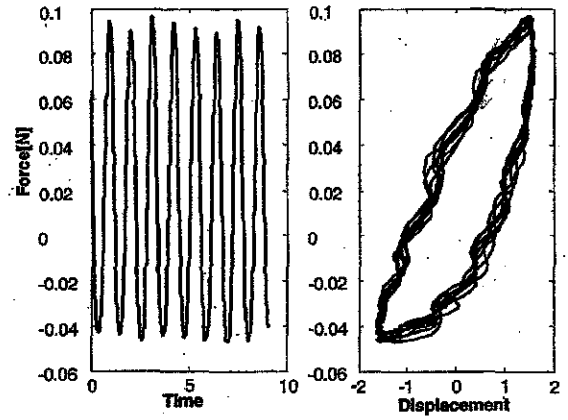

Figure 4. *In-vivo* sinusoidal force response from the lower esophagus at 1.0Hz.

4. Concluding remarks

What we have presented in this paper is work in progress. We are in the process of incorporating the material response data from these experiments in a surgical trainer for laparoscopic Heller myotomy [7]. Efforts are being made to determine the effects of boundary conditions on the organ force response. We are also in the process of quantifying the effects of anisotropy on tissue response.

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