Proceedings of the ASME 2007 Summer Bioengineering Conference (SBC2007)
June 20-24, Keystone Resort & Conference Center, Keystone, Colorado, USA

SBC2007-176645

VISCOELASTIC CHARACTERIZATION OF PERFUSED LIVER: INDENTATION TESTING AND PRELIMINARY MODELING

Amy E. Kerdok (1), Robert D. Howe (2), Simona Socrate (1)

(1) Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA

(2) School of Engineering and Applied Sciences
Harvard University
Cambridge, MA

INTRODUCTION

Computer-aided medical technologies are currently restricted by the limited understanding of the mechanical response of solid abdominal organs to finite loading conditions typical of surgical manipulation [5]. This limitation is a result of the difficulty in acquiring the necessary data on whole organs. To develop a constitutive model capable of predicting complex surgical scenarios, multiple testing modalities need to be simultaneously obtained to capture the fundamental nature of the tissue's behavior under such conditions. *In vivo* tests are essential to obtain a realistic response, but their inherent difficulty and unknown boundary conditions makes them an impractical approach. *Ex vivo* tests are easy to control, but the response is unrealistic. A perfusion apparatus was previously developed that obtained near *in vivo* conditions for whole livers while allowing the ease of *ex vivo* testing [3]. This work presents the results from complete viscoelastic testing of whole-perfused livers with surgically relevant time-dependant indentation loading profiles to 35% nominal strain. These results will aid in the development of a constitutive model for the liver whose parameters can be related to the physical constituents of the tissue. As an intermediate modeling step, a 1D rheological modeling tool was used to identify the form and initial parameters for a constitutive model.

METHODS

Livers from five pigs (57.8 ± 23 kg mean mass) were tested using the perfusion apparatus from [3], with the outlet (inferior vena cava) serving as a means of hydrating the organ surface. The perfusate was changed from [3] to include 5% Dextrose Lactated Ringers Solution and 6% Hetastarch (Henry Schein, Melville, NY), and the system was redesigned to allow for better temperature control and oxygenation with room air. A preliminary study with histology showed that the new system was capable of maintaining the mechanical integrity of the liver for up to 6 hours.

In addition to the creep device in [3], a motorized indentation system was developed (TestBench Series, EnduraTEC Systems Group, Bose Corporation). The system commanded displacement with ± 6.3 mm travel (LVDT 3.9 μm RMS noise), and recorded force using a 22 N submersible load cell (13 mN RMS noise) and acceleration using a ± 50 g accelerometer (0.5 g RMS noise). A custom 12 mm diameter flat-ended indenter provided low-level suction at the surface of the liver. This allowed for a non-slip boundary condition, and ensured that contact was maintained throughout testing.

The appropriate test protocol was determined based on studies from Brown and Rosen's BLUE-Dragon device [2, 4], which revealed that surgeons grasp with less than 10 N of force at frequencies typically less than 2 Hz. Therefore, to ensure complete viscoelastic characterization at surgically relevant rates and loads, three different tests were carried out. First, a series of 12 sequential loading and unloading displacement ramps at constant rates (three each at 0.2, 2, 20, and 40 mm/s) to 35% nominal strain (displacement/initial thickness) (corresponding to 0.01, 0.1, 1, and 2 Hz) were conducted. Particular attention was paid to the first load, as surgeons do not precondition tissues prior to manipulation. The series were repeated four times allowing for each rate to be the first load.

Second, stress relaxation tests were done at the same location. Fast displacement ramps (~500 mm/s) were applied and then held for 1200 s while force was recorded. Finally, 3600 s creep tests using a 32.5 g load were simultaneously conducted on a different location. Before conducting a new test at the same location, the tissue was allowed to recover a length of time equal to the duration of the previous test.

RESULTS

Figure 1 shows the force versus displacement response of the first three indentations at each of the four rates for a representative liver (one whose dimensions most closely represented the mean). The results reveal a nonlinear response with hysteresis, strain rate sensitivity, and a decrease in both peak force and hysteresis with repeated indentation. Stress relaxation across all livers resulted in peak forces of 8 ± 2.6 N and equilibrium forces of 0.76 ± 0.6 N. Creep results were similar to those in [3] resulting in an equilibrium nominal strain of 52 ± 5%.

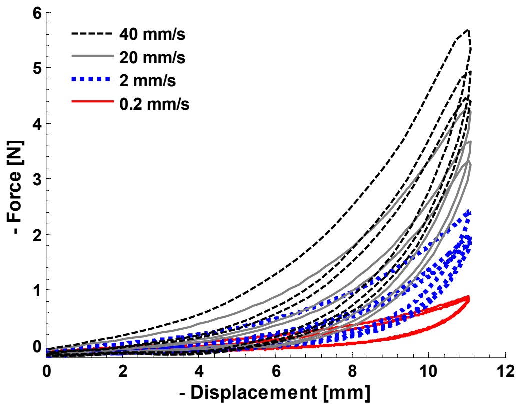

Figure 1: Force versus displacement data for a representative liver showing three consecutive indentations at 0.2, 2, 20, and 40 mms.

Before complete 3D modeling efforts are carried out, we propose an intermediate step where the material response in a single mode of deformation (indentation) is modeled within a 1D nonlinear rheological framework. We have developed an analytical tool that explores the form and the response of common configurations for viscoelastic models and allows for linear or nonlinear constitutive relations to be used to describe the elastic and dissipative elements.

The form of the model and preliminary values for the constitutive parameters were determined by using the three sequential indentations in Figure 1 at 40 mm/s, converted to nominal stress and strain, and the equilibrium relaxation response. The modeling approach was validated by predicting stress relaxation history and the full series of 12 indentations. A viscoelastic solid with a nonlinear spring (inverse Langevin formulation with initial modulus μ_o, limiting modulus μ_{lim}, locking stretch λ_L) in series with a nonlinear Voigt model comprising a linear elastic spring (E) in parallel with a 3-parameter (m, S_0, α) nonlinear dashpot [1] is shown to represent the data well (Figure 2). Preliminary values for the parameters are: μ_o= 3.05 kPa, μ_{lim}= 800 kPa, λ_L= 1.39, E= 7.9 kPa, m= 1.413, S_0= 74 kPa, and α= 0.019.

DISCUSSION

This work presents the methods and results of complete viscoelastic mechanical testing of whole perfused livers to finite deformations typical of surgical manipulations. Preliminary 1D constitutive modeling suggest that a nonlinear viscoelastic formulation is capable of capturing the salient features of the data: nonlinear load/unload, hysteresis, strain rate sensitivity, and stress relaxation. While this technique relies on a drastic simplification of the complex 3D indentation process, reducing the data to nominal 1D time-stress-strain histories, it is useful for defining the appropriate constitutive framework. The parameters identified here are not optimized but can serve as an initial estimate for future 3D constitutive modeling efforts. Future work will utilize this complete experimental data set to develop a 3D constitutive model integrated in a finite element model of the testing configuration. Material parameters will be identified by solving the inverse problem using a nonlinear optimization scheme that minimizes the mean square error between the predicted time-force-displacement response and the data. With a model derived from this complete set of data, surgical scenarios that are difficult to experimentally reproduce can be realistically modeled.

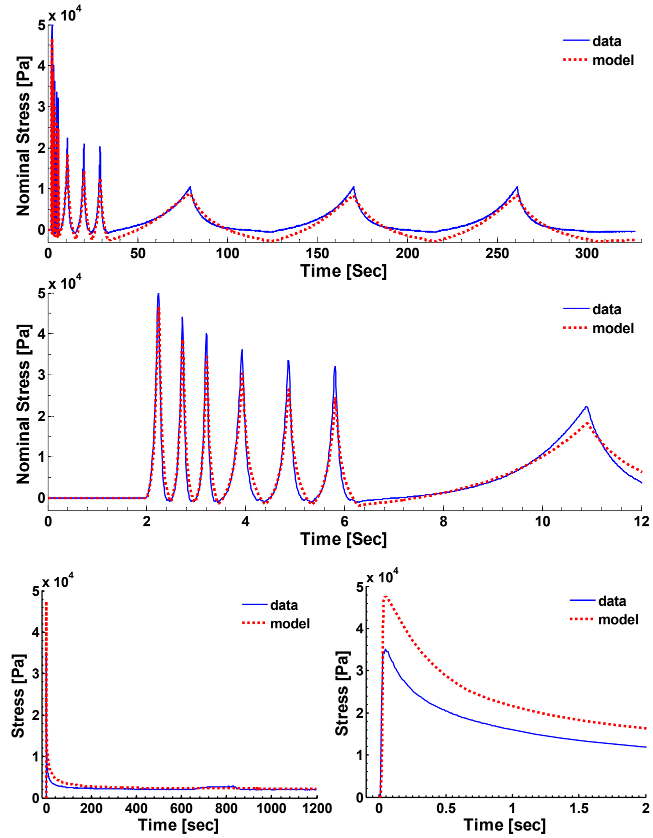

Figure 2. (Top, Middle) Nominal stress versus time for 12 consecutive load/unload indentations at 40, 20, 2, and 0.2 mm/s, and the 1D model response. (Bottom) Stress relaxation data and model prediction.

REFERENCES

1. Bergström JS, Boyce MC. Constitutive Modeling of the Time-Dependent and Cyclic Loading of Elastomers and Application to Soft Biological Tissues. Machanics of Materials 33: 523-530, 2001.
2. Brown JD, Rosen J, Chang L, Sinanan MN, Hannaford B. Quantifying Surgeon Grasping Mechanics in Laproscopy Using the Blue DRAGON System. In: Medicine Meets Virtual Reality, Newport Beach, CA, 2004.
3. Kerdok AE, Ottensmeyer MP, Howe RD. The Effects of Perfusion on the Viscoelastic Characteristics of Liver. Journal of Biomechanics 39: 2221-2231, 2006.
4. Rosen J, Brown JD, Chang L, Barreca M, Sinanan M, Hannaford l. The BlueDRAGON - A System for Measuring the Kinematics and Dynamics of Minimally Invasive Surgical Tolls In-Vivo. In: IEEE International Conference on Robotics and Animation, Washington, DC, 2002.
5. Szekely G, Brechbuhler C, Dual J, Et. a. Virtual Reality-Based Simulation of Endoscopic Surgery. Presence 9 (3): 310-333, 2000.