Finite Element Analysis of Liver Tissue Modeled Using Micro-CT

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ABSTRACT
One important question for less invasive surgical techniques, such as laparoscopy, is the behavior of the tissue of interest. Non-destructive approaches to determine material properties are of particular benefit. This paper considers the material properties of lamb liver via spherical indentation and finite element analysis. The indentation is performed under a series of step loads with a non-contacting laser displacement sensor monitoring indentation depth. The liver is also monitored using a high resolution imaging technique called micro computed tomography (micro-CT), which can create accurate 3D models and provide information about the shape of the indented surface. The 3D model from micro-CT is meshed using the NetGen software package. The load-displacement data is then compared to a finite element model in ANSYS based upon the meshed liver. Different approaches to building the model to reduce computational time are discussed. The optimal viscoelastic material properties of the liver tissue are obtained by comparing the experimental load-displacement data with that of the finite element model.

INTRODUCTION
The characterization of the material properties of biological tissues is highly useful to surgeons and tool makers. The surgeons need to know beforehand how the organs behave during surgery and the tool makers need the information to design appropriate tools for the surgeons. Most of the studies of biological materials are performed on animal organs due to the lack of availability of human tissues. However, certain groups did perform experiments on human tissues. Carter et al. [1] and Kauer [2] performed in vivo experiments on human liver and human uteri respectively. Yeh et al. [3] performed ex vivo tests on human liver specimens and came up with the material properties. The ex vivo experiments are performed on tissues removed from the body while the in vivo experiments are performed within the body of the human or animal. The advantage of in vivo experiments is that the tissues are intact in the right orientation and provide accurate material properties. However, there are certain disadvantages to this method. The use of sophisticated tools and data collection systems is limited due to the space restrictions and most of the in vivo experiments are conducted using hand held probes inserted into the body through tiny insertions on the skin. Samur et al. [4] have reported that the data obtained from the tests performed on live animals contain heavy noise due to the breathing and other internal processes within the body. The data is hard to interpret unless the magnitude of load or deformation applied is considerably larger than the noise being generated. This problem has led researchers to euthanize the animals before performing in vivo tests. Brown et al. [5] reported that the elastic properties of a porcine liver do not show a considerable change within 3 hours of euthanizing the animal; however, the stress relaxation behavior varies as the dead tissues tend to stiffen over time. Most researchers perform experimentation on animal tissues and try to relate the results to human tissues. Ottensmeyer [6] and Valtorta [7] performed in vivo and ex vivo tests on porcine liver and came up with vastly varying material properties. In this paper, the tissue in study is the liver of a lamb. Image segmentation is used to develop accurate 3D models of the specimens [8]. Indentation tests are performed on the lamb liver tissue and the material properties are obtained using an inverse finite element solution using the ANSYS software. A 2D axisymmetric model is first used to obtain the viscoelastic material properties of the liver. Various researchers have used this technique to obtain the material properties[4,9,10]. Various combinations of elastic,
viscoelastic and hyperelastic material models are studied and the best set of material properties are used to run the 3D simulation of the liver. The finite element results are compared with the image segmentation results to validate the accuracy of the model.

EXPERIMENTAL SETUP

Two types of experiments are performed on the lamb liver. The displacement control tests and the load control tests. For both the experiments the specimen is prepared in the same way.

The liver sample is cut with a circular cutter made to the same diameter as the beaker in which the specimen is to be placed, so that there would be no movement along the edges of the sample. Figure 1 shows the liver sample and the circular cutter.

![Figure 1. Lamb liver cut to the beaker size using a circular cutter](image)

The displacement controlled tests are performed using a Dynamic Mechanical Analyzer (DMA). The DMA has precise displacement control and displacements can be applied at a required rate and the corresponding forces obtained are monitored. Indentation tests are performed using a 3/8ths inch indenter spherical diameter at different displacement histories.

The load control tests are performed using a setup as described below. The glass beaker is placed in a cylindrical acrylic casing which has a clamp at the bottom. An aluminum indenter assembly is placed on the top of the casing. The assembly consists of a circular platform with an indenter passing through the center. The indenter can mover vertically through the center of the platform so that the tip of the indenter can be moved to the required position. The platform supports the loads applied during the tests. A lever is connected to the platform and a balancing weight is attached to the lever such that the weight of the assembly can be balanced by moving the balancing weight along the lever. A laser displacement sensor is placed above the assembly such that the laser beam is projected directly onto the tip of the indenter. The purpose of the sensor is to measure the displacement of the indenter during the test. The laser sensor is connected to a computer through a data acquisition card which transfers data during the test. The output of the sensor is voltage which relates to the distance moved by the indenter. The data acquisition software Labview is used to collect the data. The whole assembly is placed in the MicroCT machine. The assembly is shown in Figure 2.

![Figure 2. Setup for load control tests](image)

The MicroCT machine is used to capture the shape of the specimen during the tests. The specimen (the whole assembly) is clamped to the rotating table of the MicroCT and X-Rays are projected onto the specimen as it rotates about its axis. The x-rays capture the images in segments from top to bottom of the specimen. The tests are performed by applying different loads on the top of the specimen.
**IMAGE SEGMENTATION**

The images taken by the x-rays during the test are stacked up in order and a 3D model of the liver sample is obtained by a technique called image segmentation. A few of the x-ray images are shown in Figure 3.

![Figure 3. X-ray images of the specimen taken during the load control tests.](image)

The output of the image segmentation process is the data file containing the surface mesh points of the 3D liver sample in STL format (raw unstructured triangulated surface by the unit normal and vertices of the triangles using a three-dimensional Cartesian coordinate system). The imaging technique can also be used to enhance the quality or refine the 3D model of the sample. In this case, the irregularities of the sample which are really irrelevant to the analysis and can cause potential converging problems during analysis are removed during segmentation. Figure 4(a) shows a sample 3D model and Figure 4(b) shows the removal of irregularities on the outer surface of the sample.

![Figure 4. (a) 3D model generated by segmentation. (b) Smoothing the edges of the sample](image)

The STL output is loaded into a mesh generating software called NetGen which is then used to create different mesh densities. Different levels of mesh can be created based on the requirement of the analysis. The different mesh densities obtained from Net Gen are shown in Figure 5.

![Figure 5. 3D models with (a) coarse (b) moderate and (c) fine meshes](image)

**FINITE ELEMENT MODELING**

The finite element modeling of the liver is performed using ANSYS. A 2D axisymmetric model having approximately the same width and thickness of the actual sample is modeled using Plane 182 elements. Plane182 elements can be used with hyperelastic and viscoelastic models for large strain analysis. The spherical
The indenter is modeled as a rigid line with a pilot node at the center of the sphere. Contact elements are used to model the contact region between the indenter and the sample. The viscoelastic material properties are defined as a Prony series with four Prony terms while the hyperelastic properties are defined by the Neo-Hookean model. The initial elastic modulus and Poisson’s ratio are assumed (from values provided by various researchers) as 300KPa and 0.485 respectively. An inverse finite element analysis is done to match the experimental results to the simulation results by minimizing the error between the sets of results. The initial experimental data set used is that of a displacement controlled test shown in Figure 6. The displacement is ramped up to a value of 5 mm in 1 second and is held constant for 10 seconds. The force relaxes with time which shows that viscoelastic properties are required to model the specimen.

![Figure 6. Plot of Force and Displacement for a displacement control test](image)

The model is meshed as shown in Figure 7. It contains 256 total elements and 100 elements in the immediate vicinity of the indenter. Different mesh densities have been tried out, and the best mesh available based on the computational time of the analysis is chosen to carry out the rest of the 2D analysis.

![Figure 7. Mesh of the 2D model of liver sample](image)

The Kernel function to define the viscoelastic material properties is given by:

\[
G = G_\infty + \sum_{i=1}^{n} G_i \exp \left( -\frac{t}{\tau_i} \right)
\]

where, \(G_\infty, G_i\) = shear elastic moduli, \(\tau_i^G\) = Relaxation times for each Prony component.

The material properties for PLANE182 elements are defined by a relative modulus which is given as
\[ \alpha_i^G = \frac{G_i}{G_0} \text{ where } G_0 = G_\infty + \sum_{i=1}^{n_0} G_i \]

\( G_0 \) is the initial shear modulus. The Bulk modulus, \( K_0 \) of the material also needs to be defined for the material and it is assumed to remain constant with time. The elastic modulus \( E_0 \) is defined for the material and it is related to the shear and bulk modulii through the following relationships.

\[ G_0 = \frac{E_0}{2(1+\nu)} \quad K_0 = \frac{E_0}{3(1-2\nu)} \]

The hyperelastic material properties are defined using a Neo-Hookean model which is defined by the strain energy potential function \( W \), given by

\[ W = \frac{\mu J}{2} (I_1 - 3) + \frac{1}{d} (J - 1)^2 \]

Where, \( \mu \) is the initial shear modulus (same as \( G_0 \)), \( d \) is the material incompressibility parameter \((2/K_0)\), \( J \) is the volume ratio and \( I_1 \) is an invariant of the Cauchy-Green deformation tensor.

For the 2D model of the liver, four Prony series terms are defined \((n_G = 4)\). An initial elastic modulus of 300MPa and a Poisson’s ratio \((\nu)\) of 0.485 (nearly incompressible) are assumed as the starting properties of the finite element model. The values of \( \tau_i^G \) are defined as \( \tau_i^G = \tau_0 \) \((\tau_{\text{scale}})\) where \( \tau_0 \) and \( \tau_{\text{scale}} \) are set at 0.25 and 3.42 respectively for the above set of data. \( G_i \) is defined as \( G_i = \text{Gamma}(G_\infty G_{\text{inf}}) \) where \( G_{\text{inf}} = (F_{\text{max}}/F_{\text{min}})G_0 \) and \( F_{\text{max}} \) and \( F_{\text{min}} \) are the forces at the end of loading and end of relaxation respectively. \( G_0, G_{\text{inf}} \) and \( \text{Gamma} \) values are optimized to minimize the error between the experimental and finite element data [9].

Material properties are defined in 3 different ways to determine the best material model that fits the experimental data. In the first case, a small-deflection analysis is performed using the viscoelastic material properties in conjunction with the linear elastic properties. However, the fit between the experimental data and the finite element data is not great with a RMS error of 6.87% of the maximum load during the test. In the experiment performed, the linear displacement is about 12% of the specimen thickness which cannot be captured with a small-deflection analysis as seen from the results. In the second case, a large deflection analysis is performed using the same combination of viscoelastic and linear elastic material properties as in the first case. The fit between the experimental data and FEA data improved from the previous case and the RMS error reduced to 3.4% of the maximum load. In the third case, the viscoelastic properties are used in conjunction with hyperelastic properties defined by the Neo-Hookean model. A large-deflection analysis is performed (small-deflection analysis not possible with hyperelastic material properties). The fit between the experimental and experimental data vastly improved over the previous 2 cases with an RMS error of 2.56%. The material properties obtained from various cases are shown in Table 1.

<table>
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<th>Case</th>
<th>( G_0 ) (MPa)</th>
<th>( G_{\text{inf}} ) (MPa)</th>
<th>Gamma1</th>
<th>Gamma2</th>
<th>Gamma3</th>
<th>Gamma4</th>
<th>RMS Error (N)</th>
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<td>0.2500</td>
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<td>0.1250</td>
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<td>0.141</td>
<td>0.5060</td>
<td>0.2585</td>
<td>0.1350</td>
<td>0.1005</td>
<td>1.4230</td>
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<tr>
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<td>0.121</td>
<td>0.5050</td>
<td>0.2553</td>
<td>0.1297</td>
<td>0.1100</td>
<td>1.0677</td>
</tr>
</tbody>
</table>

Table 1. Material Properties obtained from different material models

The fits of the experimental data with the FEA data for the 3 models are shown in Figure 8. Part (a) shows the fit of the loading data and (b) shows the fit of the relaxation data. It can be observed that the loading portion of the data is the most difficult to fit. The model containing both viscoelastic and hyperelastic properties had the best fit of the load data while the model where a small-deflection analysis is performed with viscoelastic and linear elastic properties had the worst fit among the three cases. However, for the relaxation part of the data, all three models provided good fits. When both the loading and relaxation fits are combined, the visco-hyperelastic model has the minimum RMS error out of the 3 models studied. Hence, it is used for all further analyses of the liver material.
The results obtained from the best material model, that is the model containing both the viscoelastic and hyperelastic properties are shown in Figure 9 through Figure 11. Figure 9 shows the stress in the material in the direction of displacement. The maximum stress occurred just under the indenter as expected and the maximum value of stress has reduced by 2.3 times during relaxation (over 10 sec). The stress away from the region of indentation is constant and negligible (almost 0 MPa) which shows that the material away from the area of indentation is not affected during the test. The same inference can be obtained from Figure 10 which shows the VonMises stresses in the sample at the peak load and at the end of relaxation. The maximum VonMises stress occurred under the indenter and is reduced by 2.6 times during relaxation. The VonMises stresses away from the region of indentation remained negligible. Figure 11 shows the strains in the direction of displacement. The maximum strain occurred not just below the indenter, but at a region a lower than the tip of the indenter. The plot shows a small region adjacent to the indenter having a positive strain which indicates that the material in that region was displaced in the opposite direction during indentation. The maximum strain almost remained constant during the test as it is a constant displacement test and the strain away from the indentation region remained insignificant.
The properties obtained from the 2D models are used in the 3D analysis of the liver. In the 3D analysis, the exact shape of the top surface is modeled (with the help of image segmentation explained above). The indenter is placed at different locations and load controlled analysis is performed. The FEA results are compared with the experimental results. As the load control tests have 3D models developed using Image segmentation, the final deformed shape of the specimen can be compared between segmentation and FEA models. Figure 12 shows a sample set of data where a force of 40 gmf is applied on the specimen. The displacement is monitored during the experiment and it is observed to be increasing with time. Figure 13 shows the 3D model of the liver sample in ANSYS. The different experimental cases are simulated using the properties obtained from the 2D model and the results are compared to the experimental results.
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REFERENCES


