Dynamic measurement and modeling of soft tissue behavior with an indentation device using indenters of various shapes

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Keywords: Dynamic measurement; Mathematical model; Viscoelasticity; various shaped indenter

Abstract. In this paper, we performed the dynamic measurement and modeling of soft tissue with removing samples from the main body to characterize the soft tissue properties for medical simulations. The measurement method made various patterns of normal surface indentations of a soft tissue. Next, the reaction forces through the indenter were measured using a force transducer. From the force-displacement profile, the nonlinear properties were observed in a relatively small deformation range and the frequency responses of the tissue were obtained using a series of sinusoidal indentations below 3 Hz. We developed a viscoelastic model of the tissues from the recorded force-displacement profiles, from which we can develop a model to predict the behavior of the tissues. The developed model, combined with the anatomical model, could provide a visible deformation and haptic feedback for virtual reality based medical simulations.

Introduction

Due to recent developments in the medical imaging and communication technologies, the methods of medical training and diagnosis have evolved rapidly. The concept of surgery has also changed as minimally invasive procedures were used and surgical robots were born. One of the new concepts is a VR based medical simulation. Traditionally, surgeons have acquired medical skills through practice on living animals, cadavers, and even on patients. However, such processes are inevitably followed with financial burdens, massive animal sacrifices, and ethical controversies. In order to circumvent these problems, many researchers are currently developing VR based medical simulation with accurate information on the organ and electromechanical devices. This simulation enables the indirect acquisition of complicated surgical skills that are otherwise risky and difficult to earn through surgery on real patients. To establish it, anatomically and physically accurate models of living organs are required. For this purpose, it is essential to measure mechanical properties of soft tissues. In previous research by Sakuma \textit{et al.}, mechanical properties of porcine liver tissue were measured under compression and elongation load [1]. Schwartz \textit{et al.} measured the soft tissue \textit{in vitro} and verified that soft tissue displays nonlinear viscoelasticity using indentation devices [2]. Ottensmeyer \textit{et al.} showed that the soft tissue \textit{in vivo} shows nonlinear viscoelasticity [3]. Valtorta \textit{et al.} displayed the characteristics of viscoelastic materials using the dynamic measurement of soft tissue with a torsional resonator device [4].

In this study, a dynamic indentation device (DID) with various shaped indenters was built and the mechanical properties of a porcine liver were measured \textit{in vitro}. Experiments on tissue phantom were performed in order to understand the viscoelastic property such as relaxation and hysteresis; then, the mechanical properties of the liver were measured. Using the results, the liver was modeled mathematically based on the Kelvin model.
Test Instrument (DID: Dynamic Indentation Device) and Validation

Characterization of the DID. The DID can apply dynamic indentations on the surface of soft tissues with two different indenters. Both indenters have a diameter of 3 mm and two shapes (round and flat). The maximum range of measurement of the DID is 9.8 kN, the displacement range of the indenter is up to 41.5 mm, and the maximum speed is 8 mm/s (see Fig. 1). The procedures to measure the mechanical properties using the DID are as follows. First, the indenter contacts the surface of the soft tissue and induces deformation to the tissue. Second, the reaction force is measured using the load cell. Finally, the mechanical properties of the tissue are obtained using modeling techniques.

Validation of the DID. The experiments on the tissue phantom (RTV silicon gel 6166: GE Silicones, Waterford, NY [3]) were carried out to validate that the DID performed as expected. The silicon gel is a well-known viscoelastic material and is called a tissue phantom due to its properties being similar to human skin. The tissue phantom is made from a mixture of two different liquids that are mixed in equal amounts in a cylindrical mold and baked in an oven at 90 degrees Celsius for one hour. From this experiment, we can validate the device by comparing it with the literature data of the same material [3] (see Fig. 3 (a)).

Liver tissue test. Fresh porcine liver tissues were obtained from a local abattoir. The test consists of three different inputs: the ramp and hold, sine, and linear chirp wave (Eq. 1). The ramp and hold was applied to model the relaxation property of the tissue. For a 2 mm input, the time response can be seen in Fig. 3(a). Sine was applied to show the hysteresis property of the tissue. In this case, we applied a sine of 1 mm amplitude and 0.5 Hz frequency (see Fig. 4). The chirp of linearly increasing frequency from 0.00001 Hz to 2.5 Hz was applied to obtain a function of the frequency response (see Fig. 5).

\[ I(t) = A \sin\left(\frac{\pi(f_0 + \Delta f) t}{\Delta t}\right), \quad \text{(A: amplitude, } \Delta f = f_1 - f_0, \Delta t = t_1 - t_0) \]  

(1)

Viscoelastic Model of Liver Tissue

Because the liver tissue shows typical characteristics of viscosity such as relaxation, it could be modeled as a viscoelastic material. Three mechanical models are used for modeling of viscoelastic tissue, namely, the Maxwell, Voigt, and Kelvin models, all of which are composed of combinations of linear springs and dashpots [5]. Since the liver tissue has shown relaxation features in the ramp and hold input experiments (Fig. 4), the Kelvin model is the most appropriate model to use for modeling the tissue.

For the Kelvin model, the governing equation can be as:

\[ F + \tau_{\varepsilon} \dot{F} = E_R (u + \tau_{\sigma} u), \quad (\tau_{\varepsilon} = \frac{\eta}{\mu}, \tau_{\sigma} = \frac{\eta}{\mu_0} (1 + \frac{\mu_0}{\mu})), E_R = \mu_0 \]  

(2)

For a suddenly applied force, \( F(0) \), and displacement, \( u(0) \), the initial condition is
When \( u(t) \) is a ramp and hold function, the relaxation function is the force that must be applied in order to produce an elongation that changes at \( t=0 \) from zero to unity and remains in unity thereafter.

\[
F(t) = E_R \left[ 1 - \left(1 - \frac{\sigma}{\tau_\varepsilon}\right)e^{-t/\tau_\varepsilon} \right]u(t) .
\]

The model was constructed with the Kelvin models arranged in parallel. Applying the experimental data to this model, Fig. 3(b) was obtained using a nonlinear least square curve fitting (lsqnonlin.m) in MATLAB.

**Results**

The *in vitro* tests were conducted on porcine livers using the DID. Our result shows that liver tissue has viscoelastic features such as relaxation (Fig. 3) and hysteresis (Fig. 4). Figure 3 shows the response of the liver tissue and tissue phantom to a ramp and hold input. When the input was applied on the surface, the reaction forces were recorded. When the assumed Poisson’s ratio was 0.4999, the young’s modulus of tissue phantom could be calculated, \( E=5.25 \text{kPa} \), using Eq. 5, whose result is similar to the result using TeMPeST 1-D [3]. In the same way, the young’s modulus of liver tissue (\( E=8.62 \text{kPa} \)) was calculated. The curve fitting of the Kelvin model seems to be a reasonable approximation method to fit the experimental result (Fig. 3 (b)). Fig. 4 shows that the liver tissue shows hysteresis loss and different reaction forces for the two indenters. In the experiment with the linear chirp input, the frequency response function is shown in Fig. 5, which displays amplitudes of 80 N/m and 67 N/m, and a phase of approximately zero.

\[
E = \frac{(1-v^2)f_z}{2a\delta_x} .
\]
Conclusions & Future Work

In this study, the dynamic measurement of soft biological tissues was performed *in vitro* with the DID. Viscoelastic properties such as relaxation and hysteresis were observed in the experiments with porcine livers. The behaviors of the frequency responses of the tissues were tested and appeared to be linear at a low frequency region. In each experiment, the shapes (flat and round) of the contact conditions of the indenters affected the reaction force. The anatomically and physically appropriate model of the tissue was developed with the Kelvin model and compared with the results of the measurements.

Future work will focus on the mechanical properties of soft tissue measuring with larger displacements and various shaped indenters. The responses to other types of strains, such as shear strain, are also going to be explored.

Acknowledgment

This work has been supported by a Basic Research Fund of the Korea Institute of Machinery and Materials (KIMM).

References


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10.4028/www.scientific.net/KEM.326-328.781