ULTRASOUND ELASTICITY MEASUREMENTS OF BEEF MUSCLE

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ABSTRACT

The goal of this work is to provide a quantitative comparison between ultrasound and mechanical techniques for measuring tissue elasticity. The biomechanical response of beef muscle and tissue mimicking gel to uniaxial compression are characterized with ultrasound derived stress-strain curves. Ultrasound estimates of the Young's modulus of elasticity for samples are computed from the slope of the initial linear region of sample stress-strain curves. Elasticity of tissue samples was independently determined from force-deformation measurements made with an Instron universal testing load cell device. Results from in vitro ultrasound elasticity measurements of beef muscle are presented. Ultrasonic elasticity measurements showed an overall 0.72 correlation with load cell measurements for tissue strains less than 2%. To our knowledge, these are the first reported comparisons between ultrasound tissue elasticity measurements and independent mechanical elasticity measurements.

1. INTRODUCTION

1.1. MOTIVATION

Changes in tissue elasticity are often strongly correlated to the onset of tissue pathology or disease. This makes tissue elasticity information extremely useful for early detection of cancer, coronary heart disease and liver cirrhosis. Some cancers such as scirrhous carcinomas of the breast, for example, appear as extremely hard nodules, while fluid filled cysts can be much softer than surrounding tissues [1]. Ultrasound imaging of tissue elasticities could provide a non-invasive and relatively inexpensive means for early detection of such cancers [2]. Atheroschlerosis and other vascular diseases are characterized by the accumulation of plaque in arteries. This can lead to vessel occlusion, increased strain on the heart and the development of serious coronary conditions. Plaque buildup can also lead to dramatic changes in the elastic properties of arterial walls. Development of high-frequency intravascular imaging probes capable of measuring arterial wall elasticity could eventually provide important diagnostic information regarding intravascular plaque buildup and possible plaque fracturing [3].

1.2. BACKGROUND

The longitudinal elastic modulus or Young's modulus of a sample of material is defined as the normal stress (force/unit area) on the sample divided by the resulting longitudinal strain (change in length/original length) on the sample

$$E = \frac{\sigma}{\epsilon} \tag{1}$$

where E represents the longitudinal elastic modulus, σ is the applied stress and ϵ is the resulting longitudinal strain defined as

$$\epsilon = \frac{\Delta L}{L} \tag{2}$$

where ΔL is the change in length (height) of the sample after a load is applied and L is the initial height of the sample. By measuring the strain for several different applied stresses, the stress-strain behavior of the samples can be characterized. Young's modulus acts as a constant of proportionality between the stress and strain on a material and it can be estimated from the slope of the curve in the linear region of the stress-strain curve.

By applying incremental uniaxial compressions to the sample, and by measuring the applied stress for multiple compression levels, discrete points of the stress-strain curve for a sample can be acquired. Cross-correlation of data windowed from digitized ultrasound A-lines acquired after each incremental compression is used to calculate the displacement of the bottom surface of the sample after compressions. The correlation technique essentially tracks the position of the endpoints (top and

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bottom) of the sample before and after each compression. By tracking the displacement of the endpoints, the thickness and incremental strain on each sample is precisely calculated.

The principle of estimating time delays from reflected ultrasound echoes has been employed in ultrasonic time-of-flight methods used to make distance or speed of sound measurements. The approach is also similar to the elastography technique [1] which attempts to estimate local Young's modulus values from a single point or stress-strain measurement in the linear region of the stress-strain curve. Once the strain is calculated and the corresponding stress measured, an estimate of the Young's modulus can be obtained. Ultrasound provides a non-invasive method for precisely measuring tissue displacements and thus tissue strains.

2. METHODS

2.1. MATERIALS

Ten beef longissumus dorsi muscle samples were obtained from a USDA select grade animal, from the Meat Sciences Laboratory, Department of Animal Sciences at the University of Illinois. Muscle sections were sliced into approximately 4 cm × 4 cm squares, with thickness ranging from 1-2 cm. Muscle samples had an angled fiber orientation leaving fibers neither parallel nor perpendicular to the sides.

Three samples of ultrasound tissue mimicking gel standoff material were also used in test measurements. Gel standoff samples were made of plasticized polyvinyl-chloride (PVC) shor value #4. Sample A was cut into a rectangular block with surface dimensions of 2.0 cm × 2.0 cm and with a thickness of 2.5 cm. Sample B was cut into a rectangular block with surface dimensions of 2.5 cm × 3.5 cm and with a thickness of 2.5 cm. Sample C was cut into a rectangular block with surface dimensions of 2.5 cm × 2.5 cm and with a thickness of 3.5 cm.

2.2. INSTRON LOAD CELL MEASUREMENTS

Sample load-deflection measurements were made using an Instron universal testing instrument, model 1122. Axial compressions were made using a circular 5.7 cm diameter aluminum punch crosshead with crosshead velocity set to 5 cm/min, chart speed set to 500 cm/min and full scale deflection on the chart set to 1 kg. The Instron crosshead was set to reverse direction when the punch reached a deformation equivalent to approximately 10% of the sample thickness. All measurements were made at room temperature ($22°C$).

A typical force-deformation curve obtained from a muscle sample with the Instron load cell device is shown in Fig. 1. The raw data produced by the Instron load cell is a plot of load (kg) versus deformation (mm). The axes in Fig. 1. have been normalized to represent stress (Pa) versus strain (dimensionless).

2.3. ULTRASOUND ELASTICITY MEASUREMENTS

Ultrasonic elasticity measurements were made using a single transducer setup. Samples were placed on the pad of a Taconic Farms model YG-700 rat scale. A 2.5 MHz circular, unfocused, 3.18 cm diameter Panametrics transducer was attached to the robotic arm of a Daedal motorized positioning system and aligned to perform uniaxial compressions. The system is computer controlled and has 5 degrees of freedom. The transducer was positioned to be in light contact with the sample. Precise axial compressions were made in 0.5 mm increments until a total deformation of approximately 5% was reached. The Daedal system had an axial motion precision of approximately +− 1 *microm*. After each incremental compression a 1025 point A-line was digitized at 50 MHz using a model 11401 Tektronix digitizing oscilloscope. Scale readings were used to compute the equivalent applied stress after each incremental compression. Data were then transferred to a Sun Sparc2 workstation. All measurements were made at room temperature ($22°C$) after Aquasonic coupling gel was applied to lubricate contact between the transducer punch and muscle samples.

2.4. DAEDAL MECHANICAL MEASUREMENTS

Daedal mechanical stress-strain values were computed from eqn (2) using a priori knowledge of the incremental compression applied by the Daedal positioning system (0.5 mm incremental compressions) and from pre compression measurement of sample thicknesses. The equivalent applied stress on samples was computed from scale readings and knowledge of sample surface dimensions. Ultrasound, Daedal and Instron tissue elasticity values were computed from the slope of the initial linear region of stress-strain curves, generated by each technique.

3. RESULTS AND DISCUSSION

3.1. MUSCLE STRESS-STRAIN CURVES

The exponential shape of the muscle stress-strain curve in Fig. 1. is characteristic of many materials including soft tissues [4]. An initial linear elastic region of the stress-strain curve was observed for tissue strains up to 2%. The Young's modulus estimated from the initial linear region of this curve was approximately 3.0 kPa. For tissue strains exceeding 10% the deformation enters the non-linear elastic region of the stress-strain curve. As the load is increased, the exponential stress-strain behavior suggests a strain hardening effect. This strain hardening has also observed in elasticity measurements of anterior cruciate ligaments, the aorta, psoas major tendon and pericardium [4].

The stress-strain curve for the muscle sample obtained from correlation analysis of ultrasound A-lines is shown in Fig. 2. The Instron and Daedal mechanical measured stress-strain curves are also overlayed in Fig. 3 for comparison. Ultrasound strain estimates showed good agreement with the Daedal mechanical strains. Young's moduli of approximately 4.5 kPa, 6.0 kPa and 3.0 kPa were estimated from the initial linear region of ultrasound, Daedal and Instron stress-strain curves respectively. The ultrasound, Daedal and Instron computed elastic moduli for 10 muscle tissue samples are shown in Fig. 3. Typical differences between ultrasound and Instron elastic moduli ranged from 10% to 50%, with a few samples producing differences as large as 100%. There was a 0.72 correlation coefficient between ultrasound and Instron measured elastic moduli values for the 10 samples measured.

3.2. PVC GEL STRESS-STRAIN CURVES

The stress-strain response of sample A measured using Instron, ultrasound and Daedal methods is shown in Fig. 4. The stress-strain curves for the 3 techniques were determined to be within approximately 35% of one another for tissue strains up to 11%.

A careful study of the effect of sample dimensions on sample stress-strain curves is important in understanding how tissue elasticity measurements can be affected by tissue sample dimensions as well as tissue material properties. The stress-strain response of samples A, B and B2 was also measured using the ultrasound, Daedal and Instron techniques. Our initial studies show that the stress-strain curves for the 3 samples with surface dimensions and sample thicknesses ranging from 2.5 cm to 3.5 cm were were within 27% of one another using all 3 techniques, for tissue strains up to 18%. The surface dimensions selected allowed the samples to fit completely under the Instron aluminum punch crosshead which had a 5.7 cm diameter. This enabled a uniform stress to be applied and reduced the possibility of stress non-uniformities at sample edges. Instron punch and sample surfaces were lightly lubricated to prevent bonding between the sample and punch.

4. CONCLUSION

The purpose of this study was to compare quantitatively, ultrasound and mechanical techniques for measuring absolute elastic modulus values. Our initial studies indicate an approximately 72% correlation between ultrasound and Instron elastic moduli based on measurements of 10 muscle samples measured using both ultrasound and mechanical methods. In addition, relative errors between ultrasound and Instron elastic moduli values were typically on the order of 50%. To our knowledge, these are the first reported comparisons between ultrasound tissue elasticity measurements and independent mechanical elasticity measurements.

Ultrasound elasticity imaging may ultimately provide information that is not currently attainable through other imaging modalities. However, problems with signal distortions due to compression, poor lateral resolution and low signal to noise environments have limited the ability of current ultrasound methods in measuring the absolute elastic moduli of tissues. Recent research has focused on the ability to produce accurate images of the relative elastic moduli of different tissues. Even if there are large errors in measuring the absolute elastic moduli of tissues, the capability to measure relative differences in tissue elasticities may still be useful for differential diagnosis.

5. REFERENCES

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Fig 1. Instron stress-strain curve

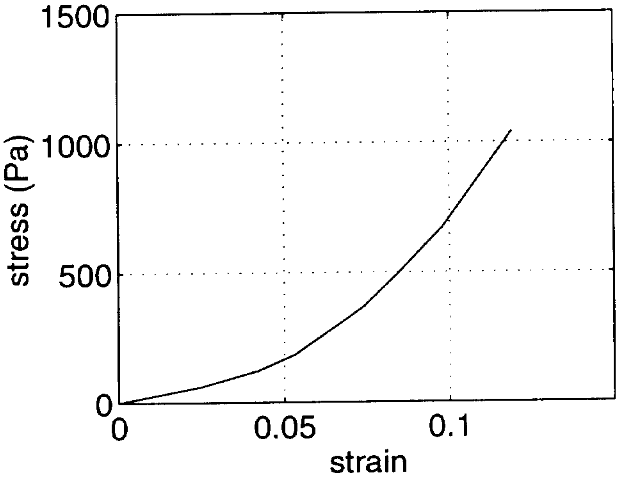

Fig 2. ultrasound- instron-. Daedal--

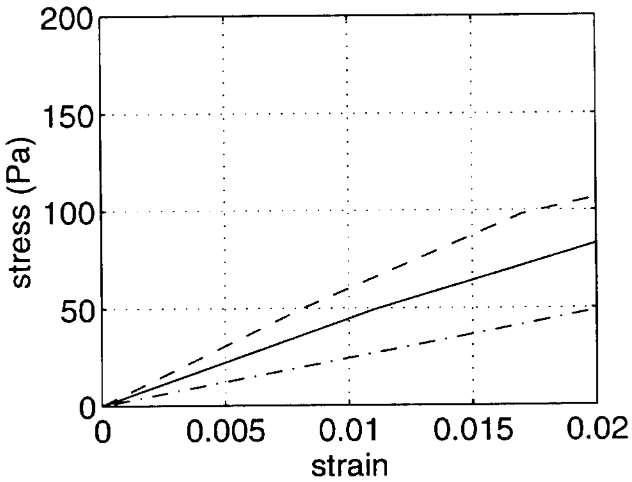

Fig 3. ultrasound- instron o

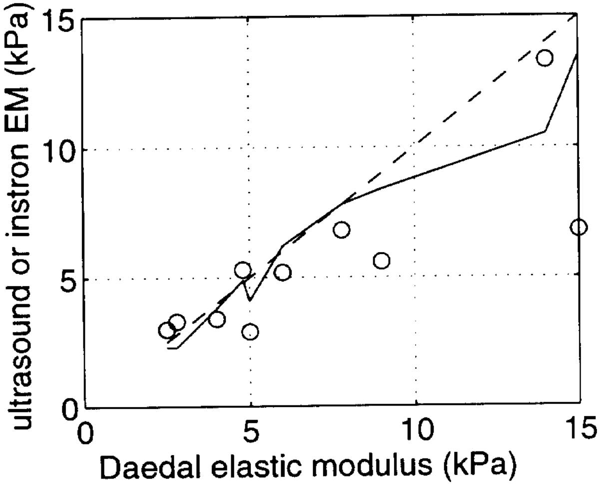

Fig 4. ultrasound- instron o Daedal--