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Research Paper

Effect of normal compression on the shear modulus of soft tissue in rheological measurements

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ABSTRACT

While the effect of normal compression on the measured shear material properties of viscoelastic solids has been already acknowledged in rheological studies in the literature, to our knowledge, no systematic study has been conducted to investigate this effect in detail to date. In this study, we perform two sets of experiments to investigate the effect of normal strain and strain rate on the dynamic shear moduli of bovine liver. First, we apply normal compressive strain to the cylindrical bovine samples up to 20% at loading rates of $v=0.000625$, 0.00625, 0.0625, 0.315, 0.625 mm/s. Second, we perform torsional shear loading experiments, in the frequency range of $\omega=0.1$–10 Hz, under varying amounts of compressive pre-strain ($\varepsilon=1\%$, 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5% and 20%) applied at the quasi-static loading rate of $v=0.000625$ mm/s. The results of the experiments show that the shear moduli of bovine liver increase with compressive pre-strain. A hyper-viscoelastic constitutive model is developed and fit to the experimental data to estimate the true shear moduli of bovine liver for zero pre-compression. With respect to this reference value, the mean relative error in the measurement of shear moduli of bovine liver varies between 0.2% and 243.1% for the compressive pre-strain varying from $\varepsilon=1\%$ to 20%. The dynamic shear modulus of bovine liver for compressive pre-strain values higher than $\varepsilon>2.5\%$ are found to be statistically different than the true shear moduli estimated for zero compressive strain ($p<0.05$).

1. Introduction

One of the most frequently used experimental methods for characterizing the viscoelastic material properties of soft tissue is the dynamic oscillation experiment. In this test, small periodic strains at varying frequencies are applied to the sample and the stress response is recorded. These small-amplitude oscillatory tests are commonly performed in shear using a rheometer. In rheological shear measurements, a cylindrical viscoelastic sample is placed between the plates of a rheometer, and some amount of compression is applied first to ensure full contact between the sample and the plates and hence to reduce the slippage. Subsequently, small oscillatory shear is applied to the sample in the linear viscoelastic range (LVR) to measure its torque response. The shear stress is then calculated from the measured torque response based on the sample geometry. Finally, the shear stress is divided by the shear strain in frequency domain to obtain two shear moduli at each frequency: one in-phase with the applied

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strain, called shear storage modulus, and the other 90° out-of-phase with the applied strain, called shear loss modulus.

Using a rheometer, the frequency-dependent shear material properties of liver (Ayyildiz et al., 2014; Kiss et al., 2004; Klatt et al., 2010; Liu and Bilston, 2000; Tan et al., 2013; Wex et al., 2013), brain (Garo et al., 2007; Hrapko et al., 2008), and kidney (Nasseri et al., 2002; Nicolle and Palierne, 2010) have been measured. Although pre-compression has been applied to the samples in all these studies, its effect on the shear material properties of the soft tissue being tested has been reported in few only. Hrapko et al. (2008) showed that increasing the normal force applied on the brain tissue samples results in overestimation of shear modulus. Tan et al. (2013) showed that the magnitude of pre-compression alters the storage shear modulus and LVR of bovine liver and recommend not applying more than 10% pre-strain in the normal direction. Despite these observations, to our knowledge, no systematic study has been conducted to investigate this effect in detail to date. In this study, we perform two sets of characterization experiments (normal compression and dynamic shear loading) to examine the effect of compression on the dynamic shear moduli of bovine liver. A hyper-viscoelastic constitutive model is developed and fit to the experimental data to estimate the dynamic shear moduli of bovine liver at zero pre-strain and then compare with the measurements performed at higher pre-strains. The constitutive models developed so far for material characterization of liver tissue have targeted to model either its linear (Ayyildiz et al., 2014; Klatt et al., 2010; Liu and Bilston, 2000; Yarpuzlu et al., 2014) or nonlinear (Nasseri et al., 2002; Nicolle et al., 2010) dynamic viscoelastic response in shear loading only, but not under the combined loading of compression and shear.

2. Materials and methods

2.1. Preparation of tissue samples

In order to obtain cylindrical liver samples, fresh bovine livers are harvested from 3 animals in a local slaughterhouse. The livers are transferred from the slaughterhouse to our laboratory while cold preserved in the Lactated Ringer's solution at +4 °C. Cylindrical tissue samples with a diameter of 25 mm and a thickness of 2.5 ± 0.5 mm are obtained from each liver using the tissue slicing and sampling apparatus developed in our earlier study (Ayyildiz et al., 2014). A total of 28 tissue samples are obtained from each liver. The samples are kept in sterile specimen cups containing Lactated Ringer's solution until the time of testing. Each sample is tested within 30 min to ensure that its material properties are not affected significantly from dehydration and all experiments for each liver are completed within 12 h after harvesting. The rim of each sample is covered with the preservation solution during the experiments and the sample is not exposed to air until the solution evaporates (Nicolle and Palierne, 2010).

2.2. Experimentation

The tissue samples are tested by a shear strain-controlled, parallel plate rheometer (Anton Paar MCR 102, see Fig. 1). In addition to a torque sensor for shear measurements, our rheometer is equipped with a force sensor, having a range of 0.01–50 N with a resolution of 0.01 N, for measuring forces in the normal direction. In order to prevent slippage between the sample and the plates, sand paper is applied to the upper and lower plates of the rheometer. The initial height of each sample is determined by moving the upper plate with a very low velocity of 0.000625 mm/s towards to the sample until a contact force of 0.1 N is reached. Then, the movement of the upper plate is stopped and the gap between the upper and lower plates is measured and taken as the initial height of the sample. Hence, in addition to the use of sandpapers, an initial normal force is applied to each sample during the measurement of its height, which makes the sample surface more flat and reduces the contact problem during the actual characterization experiments. During all measurements, temperature is kept at 24 °C by the Peltier module (P-PTD200/56/AIR) of the rheometer.

In order to investigate the effect of pre-compression on the dynamic shear response of bovine liver, normal compression and dynamic shear loading experiments are performed on the samples (see Table 1).

2.2.1. Compression experiments

The samples are compressed in normal direction up to 20% strain. Each sample is compressed only once at a loading rate of $v = 0.000625$, 0.00625, 0.0625, 0.315 and 0.625 mm/s and the force response is recorded as a function of displacement. The compression experiments are repeated 4 times at each loading rate with a different sample (see Table 1). Hence, a total of 60 tissue samples are examined in compression (4 samples per loading rate × 5 loading rates per liver × 3 livers).

2.2.2. Dynamic Shear Loading (DSL) Experiments

In order to determine the LVR of the samples, amplitude sweep experiments are performed under normal compressive strains of $\varepsilon = 5\%$, 10%, 15% and 20%, with four samples taken from each liver (4 samples per liver × 3 livers = 12 samples). The samples are oscillated in torsion at a constant frequency of $\omega = 10$ Hz while the shear strain amplitude is varied from

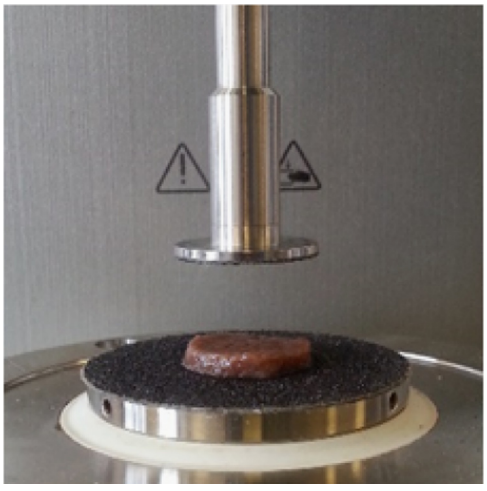

Fig. 1 – A liver tissue sample on the lower plate of the rheometer.