Dynamic Mechanical Analysis Application in Measuring the Viscoelastic Behaviour of Atrial Tissue

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Abstract

It is a challenge to provide haptic feedback for surgeons in robotic-assisted surgeries and in surgical simulations, requiring deep knowledge about tool-tissue interaction. The mechanical behaviour of tissue should be characterized and modelled in order to study the interaction between surgical instruments and tissue. Dynamic mechanical analysis is a method for characterizing the viscoelastic properties of materials. In the present paper, this method is used to characterize the viscoelastic behavior of atrial tissue. The obtained data can be used in the development of a novel method for the treatment of mitral regurgitation by using robotic-assisted surgery.

Keywords: dynamic mechanical analysis, atrial tissue, viscoelasticity.

Application Analyse Mécanique Dynamique dans la Mesure du Comportement Viscoélastique du Tissu Auriculaire

Résumé

Fournir une rétroaction haptique pour les chirurgiens est l'un des principal défis à relever de la chirurgie assistée par robot et celle des simulateurs chirurgicaux, nécessitant une connaissance approfondie de l'interaction outil-tissue. Pour étudier l'effet des instruments chirurgicaux sur les tissus, son comportement mécanique doit être caractérisé et modélisé. L'analyse dynamique mécanique est une méthode qui sert à caractériser les propriétés viscoélastiques des matériaux. Dans cette étude, cette méthode est utilisée pour caractériser le comportement viscoélastique de du tissue auriculaire issue du porc. Cette caractérisation peut être utilisé dans le développement d'une nouvelle méthode pour le traitement de la régurgitation mitrale avec technique de chirurgie assistée par robot.

Mots-clé: analyse mécanique dynamique, le tissu du auriculaire, viscoélasticité.

1 INTRODUCTION

The realistic behaviour of tissue is considered as a key requirement in tool-tissue interactions [1], since this knowledge has many applications in different areas such as surgical simulations and haptic feedback in Robotic-assisted Surgeries (RAS) [2], [3]. Providing the haptic feedback to surgeons becomes very useful in recreating the sense of touch during RAS. In this case, the surgeons feel that they have their hand in contact with patients as opposed to operating a remote mechanism [5]. For example, in the treatment of Mitral Regurgitation (MR) with RAS, the contact between heart tissue and catheter should be studied for both the creation of haptic feedback and tissue-displacement analysis [4].

To provide the haptic feedback in RAS technique, the mechanical behaviour of tissues should be analyzed and modelled. Hence, the mechanical property of the tissue should be characterized and implemented into an appropriate mathematical model [6].

Real tissues exhibit viscoelastic behaviour inherently; and their response to the force is a time-dependent displacement. Dynamic Mechanical Analysis (DMA) is one of the available techniques for measuring the time-dependent properties of tissues. In DMA method, an oscillatory force is applied to the sample—which causes sinusoidal stress—resulting in a sinusoidal strain. The quantities such as complex modulus, storage modulus, and loss modulus can be obtained by measuring: (1) the frequencies of the stress and strain waves; (2) the amplitudes of the stress and strain waves; and (3) the lag between the stress and strain waves [7].

This paper presents the viscoelastic characterization of atrial tissue of a swine heart. The characterization of the atrial tissue is important for soft tissue manipulation in treatment of MR with RAS technique.

2 METHOD

Some experimental techniques in literatures, such as uniaxial relaxation test, are widely used to determine the viscoelastic properties of biological tissues [8], [9]. Although the uniaxial relaxation test is simple, there are some deficiencies during experimental process including, accurate position control, low indentation rate, and long waiting time [10]. In particular, the relaxation test cannot be applied to determine the properties of the tissue that occur in substantial short time, due to dynamic

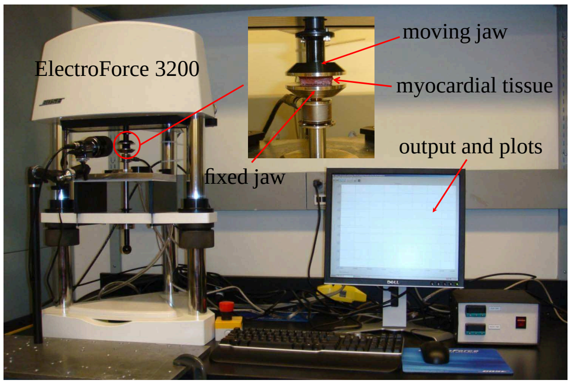


Figure 1: The position of the sample tissue between the two jaws of the device

effects. On the other hand, the DMA can overcome this problem under steady state harmonic oscillation conditions [11]. Since the short-time properties are important in RAS, the DMA is used to obtain the viscoelastic property of the swine myocardial tissue in this paper. Figure 1 shows the required test setup for performing DMA.

In the DMA test, the mechanical properties of the tissue are represented by storage modulus E', loss modulus E'' and the phase lag δ. When a sinusoidal stress is applied to the tissue, it causes a sinusoidal strain with the same frequency, but a phase lag as

$$\sigma = \sigma_0 \sin(\omega t + \delta), \quad \epsilon = \epsilon_0 \sin(\omega t) \tag{1}$$

where σ and ϵ are stress and strain in the test direction, respectively. σ_0 and ϵ_0 are amplitudes of the stress and strain oscillations, respectively, while ω being the frequency. By applying the trigonometric rules to eq.(1), the stress can be decomposed into an in-phase component and an out-phase component, namely,

$$\sigma = \sigma_0 \sin(\omega t)\cos(\delta) + \sigma_0 \cos(\omega t)\sin(\delta) \tag{2}$$

Dividing stress by strain yields

$$\sigma = \epsilon_0 E' \sin(\omega t) + \epsilon_0 E'' \cos(\omega t) \tag{3}$$

$$E' = \frac{\sigma_0 \cos(\delta)}{\epsilon_0}, \quad E'' = \frac{\sigma_0 \sin(\delta)}{\epsilon_0} \tag{4}$$

where E' and E'' are the storage and loss moduli, respectively. The storage modulus describes the ability of the material to store energy, representing the elastic effect; while the loss modulus is associated with energy dissipation, representing the viscous effect. By having the loss and storage moduli, the complex modulus can also be defined as

$$E^* = E' + iE'' \tag{5}$$

where E^* is the complex modulus and i is the imaginary unit. The phase lag δ is also calculated from the loss and the storage moduli as below,

$$\tan(\delta) = \frac{E''}{E'} \tag{6}$$

3 EXPERIMENTS

To find the tissue modulus, a test setup was designed to perform DMA on the heart tissue using a Bose ElectroForce 3200 device. First, the atrial tissue of a swine's heart was selected for testing. Since the atrial tissue is constrained inside the heart, the same boundary conditions should be recreated in the testing procedure to obtain accurate results. However, for simplification, these boundary conditions were not applied to the sample tissues during DMA. The tissue was only constrained from the top and the bottom. Figure 1 shows the position of the tissue between the jaws of the ElectroForce device. The temperature of the jaws and the tissue during test was considered constant. To test the tissue dynamically, harmonic load and displacement were applied to the tissue.

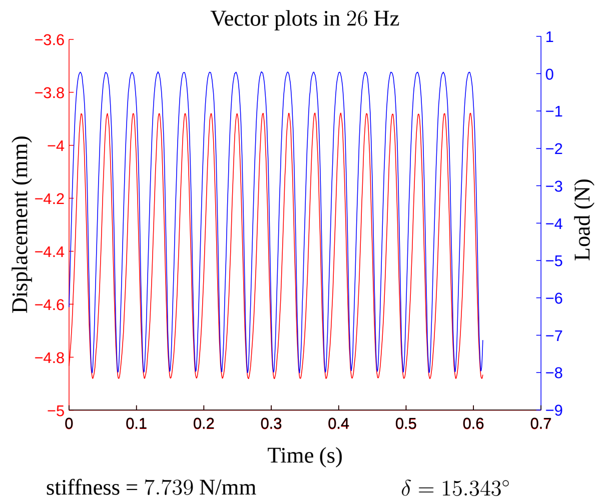
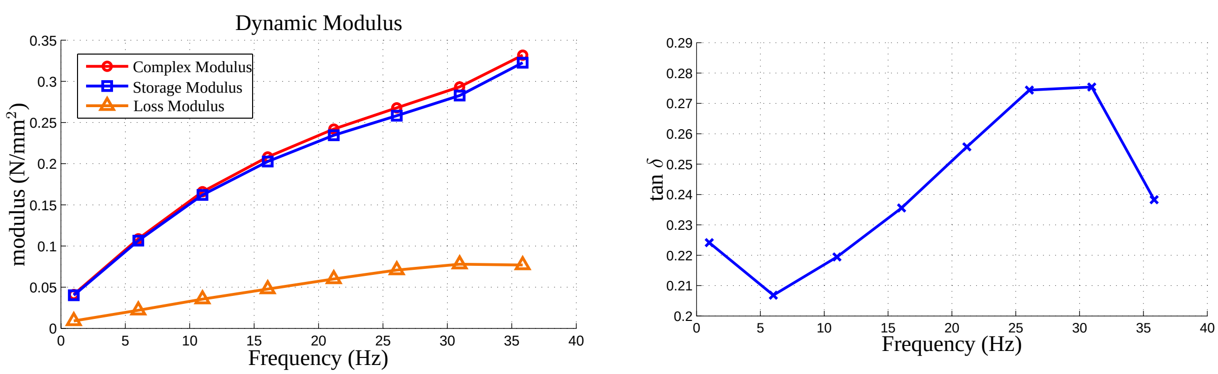


Figure 2: The scoped load and displacement data

To perform DMA, a series of test conditions were defined and applied during the test procedure systematically. A range of different frequencies, starting from 1 Hz to 36 Hz, was applied to the sample in eight different cycles. The frequency was increased by 5 Hz for each subsequent cycle, starting from 1 Hz.

Figure 2 shows the recorded response of the specimen to the applied displacement. As it can be seen in Fig. 2, the phase difference between the two scope data curves is also clear and the strain response lags behind stress by $\delta = 15.343°$. The phase lag does not have a constant value and it changes with frequency. Therefore, the value of δ should be captured and calculated at different frequencies. By performing DMA tests at different frequencies, the complex modulus, the storage modulus, and the loss modulus were found. Using Fourier transform analysis, the dynamic ampli-



(a) (b)

Figure 3: The parameters of the atrial tissue of swine's heart (a) Complex modulus, loss modulus, and storage modulus, (b) phase angle in different frequencies

tude and phase of the relevant signals were calculated and transformed to viscoelastic properties of the tissue by using Wintest software. Then, data were converted from the gathered time domain to the frequency domain. Figure 3a shows the amplitude of complex modulus, storage modulus, and loss modulus of the atrial tissue, while Fig.3b shows the captured phase lag in different frequencies.

4 CONCLUSIONS

The DMA method was used in a series of tests with different frequencies, starting from 1 Hz to 36 Hz, on several samples of the atrial tissue of a swine's heart. The results were transferred from frequency domain to time domain by using the Wintest software. Several parameters such as phase lag, stiffness, loss modulus, and storage modulus were determined for the tissue. The experimental analysis shows that the phase angle is not constant, and varies in different frequencies. The parameters can be used to model the viscoelastic response of tissue by using different techniques such as lumped-parameter models.

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