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Perspective Article

Evaluating the viscoelastic properties of biological tissues in a new way

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Abstract

In this paper, a new method for evaluating the viscoelastic properties of biological tissues such as tendons and ligaments is presented. This method obtains the complex modulus of these tissues to characterize their viscoelastic properties. With this method, the stresses and strains measured in time are first transformed (using FFT), and the complex modulus is then obtained. The complex modulus contains sufficient information about the viscoelastic characteristics of the biological tissues. With this method, the mechanical properties of biological tissues can be measured without making apriori assumptions regarding their structures, and the measurements can be made in real time.

Keywords: Viscoelastic, Biological Tissues, Complex Modulus, Fast Fourier Transform

Introduction

Materials exhibiting characteristics that are both solid- and fluid-like are categorized as viscoelastic materials[1]. Most of the biological tissues such as tendons and ligaments are viscoelastic materials. Viscoelastic materials possess time-dependent or rate sensitive stress-strain relations. In other words, the stress-strain relationship will change as the loading speed (or strain rate) changes. Since tendons and ligaments often experience stretch and extension in a wide range of strain rates in the body[2,3], knowing the viscoelastic properties of tendons and ligaments becomes very important to assessing their mechanical integrity, to preventing their injuries, as well as to maintaining the normal physical motion of the body[4,5].

Very often the viscoelastic behavior of these materials is evaluated using methods such as stress-relaxation, quasi-static and dynamic tests[6,7]. Except for the dynamic test, these tests can only provide partial information about the materials. With the dynamic test, while it is possible to obtain a full spectrum of information about the viscoelastic properties of a material, the main drawback is that the material has to be characterized at each frequency over a wide range of frequencies. Another well-known method is the quasi-linear viscoelastic (QLV) method developed by Fung[6]. Although the QLV method has been widely used to evaluate tendons and ligaments, it requires not only apriori assumptions about the reduced relaxation function and continuous spectrum of relaxation but laborious calculations as well.

A new approach is needed such that the viscoelastic properties of these materials can be evaluated quickly and completely. To meet this need, the author has recently developed a new method[8,9]. This method seeks to directly measure the complex modulus of the testing material. Here the complex modulus is the measurement of a material's mechanical property – the ratio of stress to strain – in a complex variable form. With this method, the mechanical properties of biological tissues can be measured without the need to make a priori assumptions regarding their structures, and the measurements can be made in real time. This paper discusses the advantages of this new method and compares it with other viscoelastic methods in order to bring this method to a broad application.

Viscoelasticity

The mechanical properties of many solid elastic materials can be dealt with using Hooke's law, and the hydrodynamic properties of many liquid materials can be dealt with using

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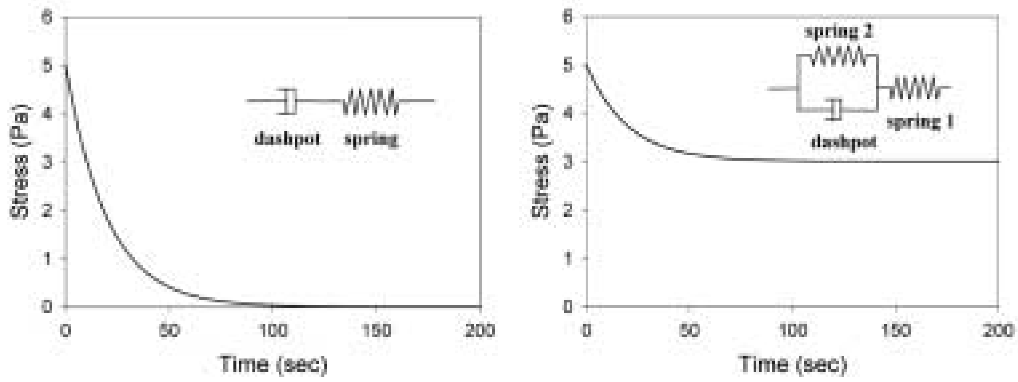

Figure 1. Left: Stress relaxation response in a two-element viscoelastic model. Right: Stress relaxation curve in a three-element viscoelastic model.

Newton's law. For viscoelastic materials, however, their stress-strain relations follow neither the Hookean deformations nor the Newtonian flow patterns alone. A combined Hookean and Newtonian method is often used to evaluate these combined solid/fluid-like characteristics. Such a method is the main subject of viscoelasticity. In the study of viscoelasticity, materials are often represented by mechanical models consisting of elastic springs and viscous dashpots. Elastic springs are to represent the elastic behavior, and viscous dashpots are to describe the fluid behavior.

As an example, a two-element mechanical model consisting of a spring and a dashpot connected in series (this model is also known as the Maxwell model) is shown in Figure 1, left. For this model, stress relaxation in the form of exponential decay will result, in response to a unit-step strain as plotted in Figure 1, left.

The limitation of this two-element model is that it can only be used to represent materials with which the stress decays to zero. For those materials with which the stress does not decay to zero, a new model is needed. In such a case, one more spring can be added to this model to form a three-element model to represent a material possessing a non-zero stress asymptote. As in the example shown in Figure 1, right, with an additional spring, the stress no longer decays to zero in its stress relaxation curve.

In these two examples, we can see that a particular mechanical model (i.e., a combination of springs and dashpots) needs to be selected to represent certain behavior of a viscoelastic material. Selecting a model to represent an unknown material can be very problematic in practice. Certainly, we could conduct a series of curve fitting with various combinations of springs and dashpots until a good fit is found. But this approach certainly will be very time-consuming, and it may even become impossible when a good fit does not exist, no matter how many trials were conducted. Thus, using stress-relaxation tests along with exponential curve fitting to evaluate viscoelastic materials is often impractical.

Besides the stress-relaxation tests, we often perform other types of tests to evaluate viscoelastic materials. One of such is the quasi-static loading test in which a strain is gradually ramped up at a certain strain-rate, and ramped down after reaching its peak. In response to this type of loading, a different stress response will result. Figure 2, left shows two stress-strain curves obtained at two different strain rates for the same three-element model. This type of test can directly reveal the strain-rate sensitive behavior of the material in its stress-strain curves. For the two stress-strain curves shown (the upper one experienced a higher strain-rate than the lower one), it is seen that a lower strain rate results in a lower peak stress and more energy loss (indicated by the wider distance between the loading and unloading curves).

Such strain-rate sensitive behavior of a viscoelastic material suggests that different stress-strain curves will be obtained if the strain rate of the test varies. This leads us to question what strain rate to use and how many rates should be used. The answer is as many as possible, if we were to fully characterize the material of interest.

This is exactly what we do in a dynamic test, where a series of sinusoidal strains with a wide range of frequencies is applied to the material, and the stress response is measured at each frequency. Because of the viscoelastic nature, two stress components (one in-phase with the applied strain and the other out-of-phase) are obtained at each frequency. By the ratio of the stress to strain at each frequency, two modulus measurements, one in-phase and the other out-of-phase, are calculated. The two moduli will form the so-called complex modulus with the in-phase modulus (also known as the storage modulus) being its real part and the out-of-phase modulus (also termed as the loss modulus) its imaginary part. The storage modulus defines the elastic property, and the loss modulus governs the viscous property of the material of interest. Figure 2, right shows the variation of the complex modulus with frequency obtained for the three-element model. The upper curve is the storage modulus and the lower one is the loss modulus. They both vary with frequency.

The complex modulus provides important information

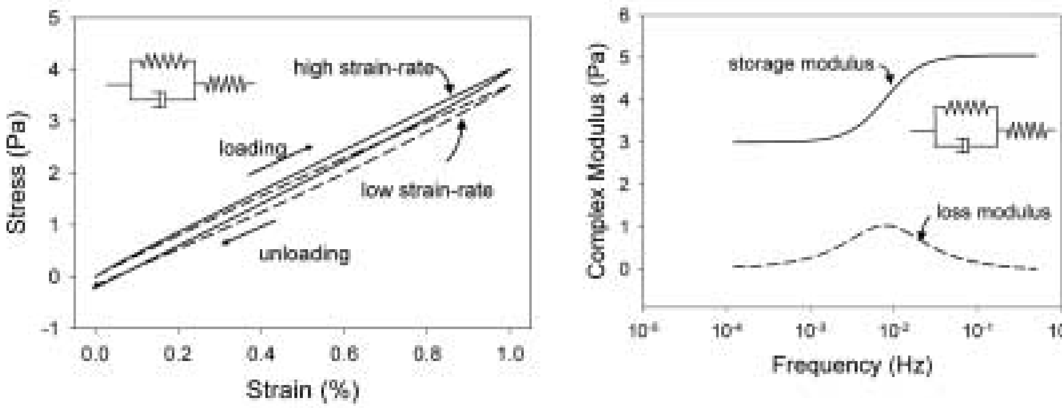

Figure 2. Left: Two stress-strain curves obtained for the three-element viscoelastic model under two different strain-rates. Right: Complex modulus spectra obtained for the three-element model under dynamic loading.

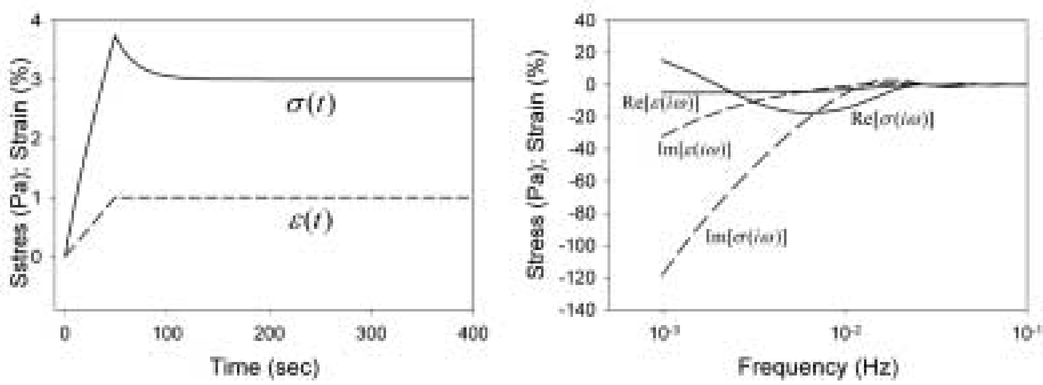

Figure 3. Left: Paired strain and stress curves measured in time for the three-element viscoelastic model. Right: the corresponding complex stresses and strains in frequency.

about the material. The entire spectrum of the complex modulus reveals the variations of the elastic and viscous properties of the material as a function of frequency, and it also provides the measurements for energy dissipation and damping[10]. So the advantage of obtaining the complex modulus is obvious. But one drawback of using a dynamic test to measure the complex modulus is that these measurements have to be made at each frequency within the range of frequencies of interest.

A new method for measuring the complex modulus

It would be ideal to be able to characterize these viscoelastic materials without pre-selecting a mechanical model, or going through a repetitive procedure. Such a method has recently been developed by the author[8,9]. Here, the main features of this new method and its advantages are discussed.

For an unknown biological tissue (say a piece of chicken tendon), instead of guessing what combinations of springs and dashpots to use, we consider the relation between the stress and strain in a similar manner as for a linear electronic system where its output is expressed as the convolution of the input and its impulse function. So the stress $\sigma(t)$ and strain $\varepsilon(t)$ of this biological tissue can be related in convolution as $\sigma(t) = \varepsilon(t) \otimes h(t)$, where $h(t)$ is the impulse response function of the material. By taking Fourier transform of this stress-strain relation and rearranging it, we have $H(i\omega) = \sigma(i\omega)/\varepsilon(i\omega)$, here $H(i\omega)$ is the complex modulus, $\sigma(i\omega)$ and $\varepsilon(i\omega)$ are the Fourier-transformed stress and strain, respectively. This analysis shows that the complex modulus of a viscoelastic material can be determined by taking the ratio of the Fourier-transformed stress and strain series measured in time.

To realize this development, we first apply a strain to the material of interest and measure the stress response as a

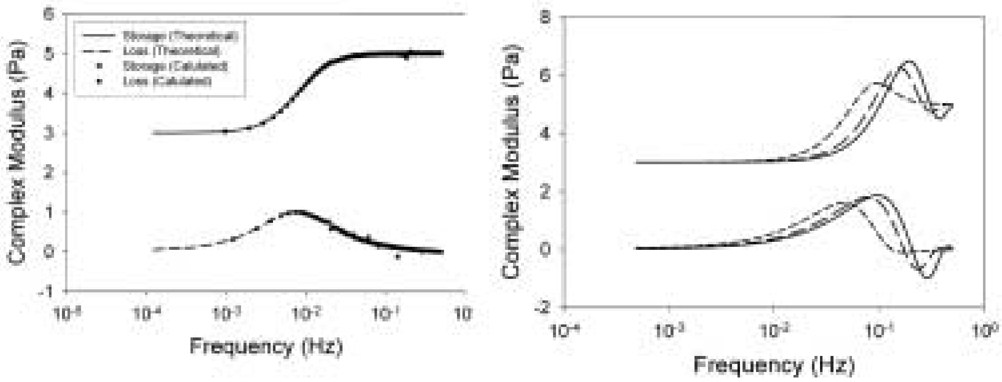

Figure 4. Left: Complex modulus calculated for the three-element model based on the present method along with theoretical solutions. Right: Complex modulus obtained for three higher orders non-linear systems.

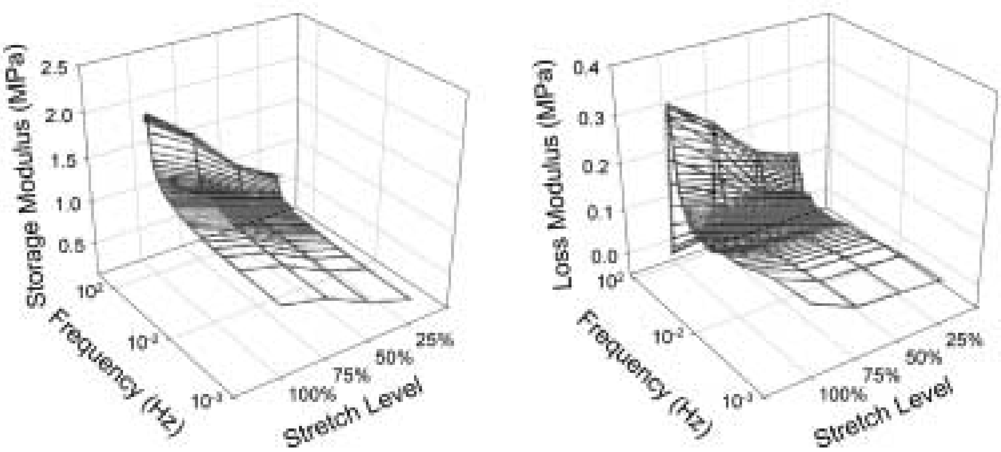

Figure 5. Left: A 3-D mesh plot of the storage modulus obtained for a non-linear polymer material at four different levels of stretch. Right: A 3-D mesh plot of the loss modulus from the same material at four stretch levels.

function of time. To the paired stress and strain variables measured in time, we perform Fourier transform to obtain the Fourier-transformed stresses and strains as a function of frequency. These Fourier-transformed stresses and strains are in complex forms. Finally, we take the ratio of the complex stresses and strains to calculate the complex modulus.

To illustrate these steps, let us look again at the three-element viscoelastic model discussed above. To make it more practical, let us apply a step strain $\varepsilon(t)$ with the initial rising portion in order to mimic a real situation (note that in a real situation it always takes time to step up a strain). The stress $\sigma(t)$ response in time is then measured. Both the stress and strain series are plotted in Figure 3, left as a function of time. By performing fast Fourier transform (FFT) to both $\sigma(t)$ and $\varepsilon(t)$, their frequency based counterparts, $\sigma(i\omega)$ and $\varepsilon(i\omega)$, are obtained and plotted in Figure 3, right (note that Re[] and Im[] represent the real and imaginary parts, respectively).

To obtain the complex modulus, we take the ratio of the complex stresses to the complex strains. In Figure 4, left, the obtained complex modulus in variation with frequency is plotted in dotted lines along with the theoretical results in solid lines: the upper curves are the storage modulus and the lower curves the loss modulus. Clearly, the calculated and theoretical results are in very good agreement. These results imply that the complex modulus of an unknown material can be measured without making any a priori assumption regarding its structure, and the measurements can be made in one test run instead of multiple runs as in a dynamic test.

It should be noted that the use of FFT in this method does not make it anything less than an experiment-based method. As we know, in most testing procedures, we rely on the measured data to calculate the intended measurands. The only difference, which sets apart this method from the rest, is that in this method these calculations are made with arrays

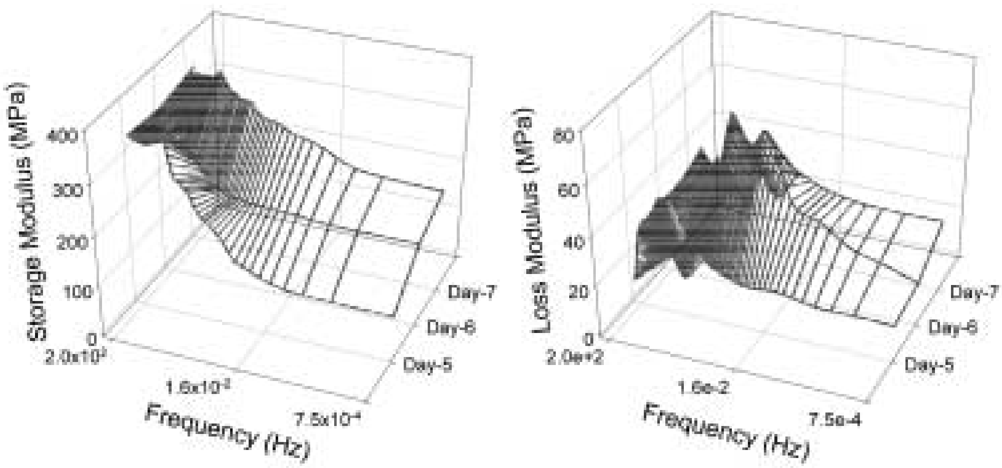

Figure 6. Left: A 3-D mesh plot of the storage modulus obtained for a viable mouse tibia at day-5, day-6 and day-7. Right: A 3D mesh plot of the loss modulus for the tibia.

of data, rather than with individual data points.

In spite of the advantages of this new method, one issue of concern is that it is a linear based technique. One question remains: is this method applicable to tendons and ligaments that are often considered as non-linear viscoelastic materials? Based upon the validity of using piece-wise linear segments to integrate non-linear curves, and that an accurate solution will result when the segment width becomes infinitesimal, it is believed that by decreasing the time interval for measuring the stress and strain this method should be able to capture the characteristics of any non-linear viscoelastic material very closely.

It was demonstrated by the author that for a non-linear material the calculated complex modulus based on this method agreed very well with the theoretical solutions[8]. Here let us apply this method to even higher orders of non-linear viscoelastic responses. For example, three cases of stress relaxation from second to fourth order in the forms of e^{-t^2}, e^{-t^3} and e^{-t^4} are examined. As shown in Figure 4, right, the upper three curves are the storage moduli for cases with increasing order from left to right, and the lower three curves are the loss moduli. As anticipated, both the storage and loss moduli for all three cases converge to their respective common values at both the low and high ends of the frequency scale. The differences in the peak values of the moduli, the locations of the peaks, and the shapes of the moduli spectra are attributed to the difference in the orders of decay, which are governed by the characteristics of these viscoelastic models.

With this method, the complex modulus of a viscoelastic material can be evaluated very quickly from a paired set of stress and strain variables measured in time, regardless of whether the material is linear or non-linear. One cautionary note for non-linear materials application is that the viscoelastic behavior of these materials depends not only on the strain-rate but also on the level of the applied strain. Thus, for non-linear viscoelastic materials it is recommended to evaluate their complex modulus with a broad range of strain levels. Figure 5 shows an example where orthodontic elastic chains made of a copolymer of polyethylene and polyurethane are tested at four stretch levels, 25%, 50%, 75%, and 100%, and their complex modulus obtained is presented in 3-D mesh plots: storage spectrum mesh on the left, and loss spectrum mesh on the right.

Using this method we could also evaluate biological materials as they grow. In Figure 6 an example is given where a viable mouse tibia is evaluated with the same level of compressive strain at three different times: day-5, day-6 and day-7. The obtained complex modulus is plotted in 3-D mesh plots: storage spectrum mesh on the left, and loss spectrum mesh on the right.

Discussion

A new method for evaluating viscoelastic materials is presented. Because of the use of FFT, high-speed sensing, and computerized data acquisition and data processing in this method, the mechanical properties of viscoelastic materials can be measured without the need to make a priori assumptions regarding their structures, and the measurements can be made in real time. This method can be applied not only to linear viscoelastic materials but also non-linear materials. This is advantageous, because most of the biological tissues are non-linear viscoelastic materials.

Because of the use of FFT in this method, the measured material properties in frequency domain will have an upper frequency limit set by the Nyquist frequency ($f_{upper} = ½\, f_{sampling}$). Thus, to push the upper limit, one needs to increase the sampling frequency (or decrease the sampling interval). In practice, the upper limit for the sampling frequency is most likely controlled by the hardware limit in data acquisition. The lower frequency limit is determined by the time duration (t_{test}) of the test ($f_{lower}=1/t_{test}$).

The measured complex modulus contains not only the mechanical properties (magnitudes of the modulus spectra) but also the material characteristics (shapes and peak locations of the modulus spectra). This method thus enables us to establish possible links between the mechanical properties and material characteristics with a single testing procedure. With this method, the mechanical properties of many biological materials, like the tendons and ligaments, can be evaluated along their growing path, or along the time period during which an external stimulatory environment is introduced to stimulate their growth. Furthermore, with the latest advances in micro/nano technologies, this method can be readily miniaturized by using micro/nano sensors and microchips (capable of handling FFT). Thus, a real-time and *in situ* evaluation of these biological materials can be achieved.

Conclusions

With the new method presented here, mechanical properties of biological tissues such as tendons and ligaments can be measured without making any a priori assumption regarding their structure, and the measurements can be made quickly. This method allows us to establish possible links between the mechanical properties and material characteristics with a single testing procedure, and to evaluate these biological materials in a real-time and *in situ* manner.

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