Viscoelastic properties of the central region of porcine temporomandibular joint disc in shear stress-relaxation.

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Abstract

In this study, shear relaxation properties of the porcine temporomandibular joint (TMJ) disc are investigated. Previous studies have shown that, in fatigue failure and damage of cartilage and fibrocartilage, shear loads could be one of the biggest contributors to the failure. The aim of the present study is to develop an evaluation method to study shear properties of the disc and to do a mathematical characterization of it. For the experiments, twelve porcine discs were used. Each disc was dissected from the TMJ and, then, static strain control tests were carried out to obtain the shear relaxation modulus for the central region of the discs. From the results, it was found that the disc presents a viscoelastic behavior under shear loads. Relaxation modulus decreased with time. Shear relaxation was 10% of the instantaneous stress, which implies that the viscous properties of the disc cannot be neglected. The present results lead to a better understanding of the discs mechanical behavior under realistic TMJ working conditions.

Keywords: Temporomandibular Joint; Soft Tissues; Viscoelasticity; Biomechanical Characterization; Experimental Techniques; Shear.

1. Introduction

Synovial joints allow various degrees of relative motion among the bones to be regulated by muscles attached to the latter (Widegren et al., 2000). Daily activity accompanies joint motion resulting in joint loads. The temporomandibular joint (TMJ), a diarthrodial synovial joint, enables large relative movements between the temporal bone and the mandibular condyle (Rees, 1954; Scapino et al., 2006). Within the joint, both the articular surfaces of the condyle and temporal bone are covered by a thin fibro-cartilaginous layer showing a very low coefficient of friction (Tanaka et al., 2004b). A dense fibrocartilaginous articular disc is located between the bones in each TMJ. The disc provides a largely passive movable articular surface accommodating the traslatory movement made by the condyle (Koolstra and Tanaka, 2009).

The TMJ disc has an important load-bearing, stress absorbing and joint stabilizing function (Barrientos et al., 2016; Fernández et al., 2013; Tanaka et al., 2008; Tanaka and Eijden, 2003). The disc is subject to various types of loading, such as sustained loading during clenching and intermittent loading during mastication (Hattori-Hara et al., 2014; Hirose et al., 2006; Tanaka et al., 2007). Stresses are divided into compression, tension and shear components. During every type of loading the disc undergoes a deformation while internal forces arise within the tissue. The viscoelasticity of such a material, as that of the disc, is the principal factor of energy dissipation (Fung, 1969). These types of tissues show different mechanism of energy dissipation that are result of the different phases in their structure: interstitial fluid flow within and through the matrix and relaxation of the solid matrix (collagen fibers and proteoglycans). Without strain energy dissipation, storage of the exceeding strain energy can lead to breakage of the articular disc and other components of the TMJ (Tanaka et al., 1999).

Since shear stress can result in fatigue, damage and deformation of cartilage, investigation of shear properties in synovial joints is of particular interest (Spirt et al., 2005; Zhu et al., 1993, 1994). Gallo et al. (2000) suggest that, during mastication, fatigue failure of the TMJ disc could result from shear stresses caused by medio-lateral translation of stress location. Therefore, data on the shear modulus might contribute to a better understanding of secondary tissue damage, such as perforation or thinning of the disc due to long-term exposure to severe loadings. It has been reported that the shear stress in cartilage is very sensitive to the frequency and direction of the loading and to the amount of compressive strain (Mow et al., 1992). However, in the literature few studies are available in which the viscoelastic properties of the TMJ disc are measured in shear stress-relaxation.

This paper may provide better insight about the possible mechanism leading to tissue fatigue and failure due to shear. Therefore, in this study the viscoelastic properties of porcine TMJ disc are investigated under shear stress relaxation, aiming at advancing in the design of biomimetic disc substitutes and in the understanding of the pathological conditions of the TMJ disc.

2. Materials and Methods

In this study, twelve healthy-looking TMJ discs from 6 pigs (age: approx. 6–7 months, gender not specified) were obtained at a local slaughterhouse (Noreña, Asturias, Spain). The protocol of the experiment was approved by the Animal Care and Use Committee at the University of Oviedo, Spain. The discs were carefully dissected immediately after the sacrifice, introduced in hermetic containers immersed in a physiologic saline solution (NaCl 0.09 g/100 ml), and frozen at -25 ºC for 3 days until the experiment was initiated for testing (Allen and Athanasiou, 2005; Calvo-Gallego et al., 2017). The discs were completely unfrozen in a refrigerator at 3-4 ºC and, then, allow to reach room temperature (20 ºC) before testing. Using a cylindrical 4.0 mm diameter tissue punch, two experimental specimens were dissected from the central region of each disc (see Figure 1).

Although previous studies have shown region-dependent mechanical properties (Fernández et al., 2013), this study is only focused on the central region, mainly due to the complexity of extracting two specimens with the necessary dimensions of the rest of regions.

All the specimens were tested in a DMA Instrument (RSA3, T.A. Instruments, USA) in unconfined shear using a shear tool (see Figure 2) at room temperature (20 ºC). The loading was applied in the antero-posterior direction, since mechanical properties of the disc, due to fiber distribution, will also be direction-dependent.

As mentioned before, two specimens of each disc were cut. In Figure 2, it can be seen that the shear-tool has a sandwich configuration and samples need to be placed at both sides of the tool. In order to test shear in antero-posterior direction, the fibers of the specimens need to be aligned with the movement of the tool (vertical direction), according to Figure 3.

To avoid the specimens’ slippage during shear loading, 600 grit sandpaper was glued to the surfaces of the shear tool. Additionally, the selected inner part of the shear tool would allow testing 2 mm thick specimens. Taking into account the average thickness value for the discs, 1.84±0.11 mm, and the real gap for testing, 1.750 mm (subtracting the sandpaper sheet thickness), an average initial value of 5% pre-strain in the compression direction was applied before testing. After previous step, a 3-min preconditioning test was performed with 1% sinusoidal strain before the subsequent shear stress relaxation test. The shear strain was applied to the specimens moving the lower part of the tool in the axial direction of the machine (vertical direction in Figure 2 and 3). Shear strain levels of the TMJ disc produced under ordinary mandibular movement have not been reported. Previous studies do not show consensus for shear strain (Lai et al., 1998; Tanaka et al., 2004a). Due to the limitations of testing the specimens under shear conditions, i.e. very low loads for strain values lower than 5% or problems of slippage for strain values larger than 10%, tests were carried out at strain levels of 5% and 8% in order to obtain the corresponding relaxation modulus.

The specific level of shear strain was produced under an instantaneous strain step and kept constant during 120 seconds for each stress relaxation test keeping the same test procedure used in previous studies (Barrientos et al., 2016).

To apply and maintain the initial value of strain during the relaxation test, the DMTA machine is equipped with a motor driven by an air bearing system, which applies the corresponding displacement at a very high rate once the strain is commanded before testing (T.A.Instruments, 2001). Loads were measured simultaneously under the specified constant strain.

3. Results

3.1 Viscoelastic properties of porcine TMJ disc in shear stress relaxation

From the experimental tests, the mean and standard deviation of the shear modulus of the TMJ disc at convenient times were calculated. The resulting curves for the 5 and 8 % strain levels are presented in Figure 4 (left and right plots, respectively).

For comparison proposals both averaged curves are plotted in Figure 5. From Figure 5, a higher shear modulus is observed for the 8 % strain level. From the results (Figure 5), a dependence of the relaxation modulus, $G(t)$, with applied strain can be observed, which is in agreement with the TMJ disc behaviour previously observed (Lamela et al., 2011).

The shear modulus obtained for both strain levels (see Figure 5) presents a large relaxation ratio. For 1 s, the shear modulus decreases about 70% while a 90 % reduction is observed for 100 s.

3.2 TMJ shear relaxation model

Due to its simplicity, even though other models could be used, generalized Maxwell model was used to fit the experimental data to the viscoelastic model represented in Figure 6, as a combination of spring and dashpot elements (Tschoegl, 2012), which can be modelled using the Prony´s series model given by the equation:

$$\mathrm{G(t)} = \mathrm{G_0}\left[1 - \sum_{\mathrm{i=1}}^{\mathrm{n_t}} \mathrm{g_i}\left(1 - \exp\left(-\frac{\mathrm{t}}{\mathrm{\tau_i}}\right)\right)\right] \tag{1}$$

where g_i and τ_i are the Prony parameters and G_0 is the instantaneous shear modulus.

To simplify the material model, as well as to take into account the dependence of the $G(t)$ with the applied strain, a unique set of Prony parameters was used to fit both shear modulus curves. This procedure profits from the fact that a simple vertical shift is observed between both material curves (see Figure 5) which could be interpreted as a proportional shift of $G(t)$ with the strain.

Two steps were used for fitting the material model. Firstly, the shear curves for the TMJ are averaged and, next, the generalized Maxwell model was applied to fit the averaged curve by means of the Prony series equation (1).

To fit adequately the experimental data, 8 Prony terms were necessary being the R-square 0.994. The parameters of the Prony series presented in Table 1 define the normalized viscoelastic curve for the material, as a function of the instantaneous modulus of the material, $\mathrm{G_0}$. In this way, the curves for the 5% and the 8% strains are gained from the fitted model, simply, by multiplying in each case equation (1), by the corresponding instantaneous modulus. Accordingly, $\mathrm{G_0^{5\%}} = 1.6205\mathrm{e}+04$ kPa and $\mathrm{G_0^{8\%}} = 1.8883\mathrm{e}+04$ kPa, for the 5 % and the 8 % shear modulus curves, respectively. The Prony series parameters with higher precision are included in the appendix.

Table 1. Prony series parameters (R^2=0.994) for the normalized TMJ shear modulus curve.

τ_i	G_i
3.17e-02	4.14e-01
1.00e-01	7.90e-02
3.19e-01	6.26e-02
1.01e+00	6.36e-02
3.21e+00	5.68e-02
1.01e+01	7.36e-02
3.22e+01	6.65e-02
1.02e+02	1.44e-01

The experimental and the analytical curves (using equation (1)) are presented in Figure 7**.** The maximum error between the experimental results and the proposed model are less than a 2% for both curves.

4. Discussion

Fatigue failure and damage of joint tissues, including both disc and cartilage, may be more linked to repeated and prolonged extension and shear motions than to the joint compression applied (Iatridis and ap Gwynn, 2004; Tanaka et al., 2003). Even when the disc slides along smooth temporal cartilage during jaw movements, shear loading of the disc and cartilage has been considered to be negligible due to almost zero friction. However, several authors support the evidence that the disc and cartilage are subjected to shear stress. For example, after prolonged clenching and grinding, only solid contact may exist between the disc and cartilages, without boundary lubrication between them, resulting in considerable shear stress (Forster and Fisher, 1999, 1996; Tanaka et al., 2001). Few studies of the behaviour of the TMJ disc under dynamic shear loads were performed in the past (Juran et al., 2013; Koolstra et al., 2007; Tanaka et al., 2004a, 2003) to evaluate the mechanical properties of the disc at different strain rates and frequencies. The present study is, as far as we know, the first, in which the shear relaxation properties of the TMJ disc in shear stress relaxation were examined. Wu et al. (2015) investigated the intrinsic viscoelastic shear properties in porcine TMJ disc, but in contrast to the present study, they applied a rotational shear loading. The present design might reproduce the actual environment in the TMJ disc.

Previous studies have shown that due to morphology, function and diet, pig discs are the closest to human discs making them an appropriate model for TMJ studies (Bermejo et al., 1993; Kalpakci et al., 2011). In this study, relaxation viscoelastic behaviour of cut porcine specimens is evaluated in antero-posterior direction at 5 and 8% shear strain levels. As a result, the instantaneous shear moduli were increased with increasing applied strain. This evidences a dependence with strain of the behaviour of the disc which is in good agreement with the general mechanical behaviour observed previously in the TMJ disc (Lamela et al., 2011; Tanaka and Eijden, 2003).The possible explanation for this increment is the stretching of collagen fibers in antero-posterior direction (Barrientos et al., 2016; Lamela et al., 2011; Tanaka et al., 2003). Furthermore, present results show that the relaxed stress of the porcine TMJ disc was approximately 10% of the instantaneous stress irrespective of shear strain amplitude. This indicates that energy-dissipation function takes place in the TMJ disc. Without the energy dissipation capacity of the disc, TMJ components including bony components and soft tissue probably fail resulting in the tissue rupture. Thus far, it is concluded that the TMJ disc plays an important role as a stress bumper during complex mandibular movements.

When comparing the compression relaxation tests (Barrientos et al., 2016; Lamela et al., 2011) with the shear relaxation tests, the present results clearly show that compression relaxation modulus is 10 times higher than shear relaxation modulus. Adam et al. (2015) investigated an image-based modelling study on the bovine caudal disc, and concluded that shear resistance between lamellae confers disc mechanical resistance to compression. This points out the relationship between shear and compressive properties of the TMJ disc. Moreover, the present results reveal that the porcine TMJ discs exhibited shorter relaxation times under shear stress relaxation than under compressive stress relaxation. This may be due to the difference of an outflow of interstitial fluid caused by pressurization of the compressed area. During shear stress relaxation, the fluid within the disc is likely to move along the stretching collagen fibers; however, during compressive stress relaxation, the disc maintains a fluid pressure because of sustained interstitial fluids within the disc. Since the load bearing functions of cartilaginous tissues are mainly provided by the viscoelastic property of collagen fiber network and the osmotic pressure due to the presence of proteoglycans (Hardingham and Fosang, 1992), the large proteoglycans and the related chondroitin sulfate might be more important to counteract compression and shear, while the collagen fibers are more important to counteract tension (Tanaka and Eijden, 2003).

Mow et al. (1980) reported about the biphasic theory, this theory is suitable for better understanding of the mechanisms involved in energy dissipation. Due to the highly heterogeneous structure of the TMJ disc, the viscoelastic approach used in this study gives a global understanding of the mechanical properties of the disc rather than the material constitutive law.

In literature, authors have used different models to characterize the viscoelastic properties of the TMJ disc (Allen and Athanasiou, 2006; Tanaka and Eijden, 2003). For large displacements, other models could be more appropriate (Fung, 1969). In this study, a generalized Maxwell model, based on Prony´s series, was applied to characterize the shear relaxation modulus of the material. Although the TMJ disc presents a strain-dependent behavior, almost the same relaxation rate is observed for the strain levels applied in the experiments (see Figure 5). This fact allows a unique viscoelastic model to be fitted where the instantaneous modulus, G_0, at the corresponding strain level must be used. The results obtained with the proposed Prony series model can be considered adequate for the shear relaxation modulus of the TMJ disc showing errors under 2%.

To be consistent with previous studies and allowed comparison (Barrientos et al., 2016; Fernández et al., 2013), some testing conditions, such relaxation time and temperature, and model parameters were chosen. Temperature affects mechanical results as higher temperatures reduce stiffness and strength of the discs (Detamore and Athanasiou, 2003).

In conclusion, the relaxation properties of the porcine disc were determined under shear in this study. A new methodology to test the disc under relaxation shear conditions was proposed. The study shows that the viscoelastic properties of the disc under shear loads cannot be neglected. Shear properties of the disc in antero-posterior direction were characterized using a unique Maxwell model. Nevertheless, this study is a first step in the shear characterization of the TMJ discs and further studies are needed to conclude on the shear behavior of the disc in medio-lateral direction, cyclic loads, pre-compression and region dependencies.

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Conflict of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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6. Appendix A

Table 1. Prony Series coefficients for the TMJ Shear modulus with higher precision

τ_i	G_i
3.171801782714793e-02	4.146791885739055e-01
1.006032675003927e-01	7.901525169602446e-02
3.190936295865514e-01	6.262266247153189e-02
1.012101763417593e+00	6.369962544203969e-02
3.210186241700431e+00	5.687840666168365e-02
1.018207464791342e+01	7.366328040806444e-02
3.229552316589736e+01	6.652140489569733e-02
1.024350000000000e+02	1.443664636944322e-01

Figure 1. Area where the specimens were cut and fiber direction.

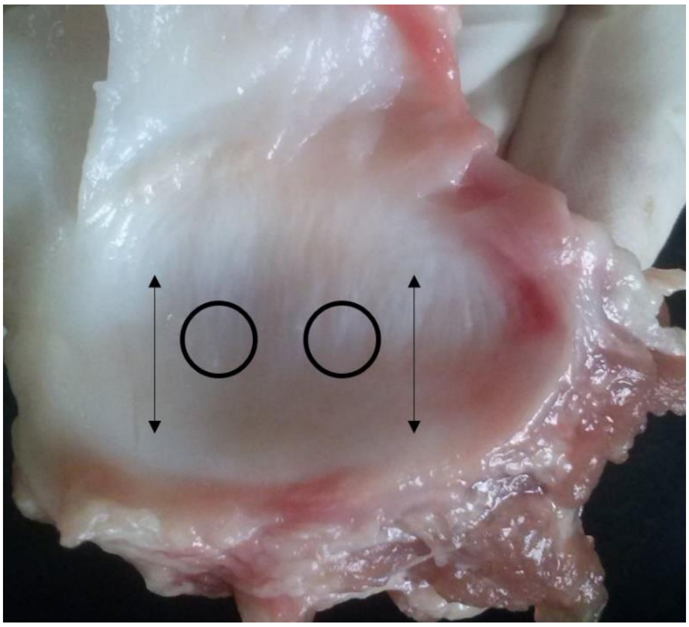
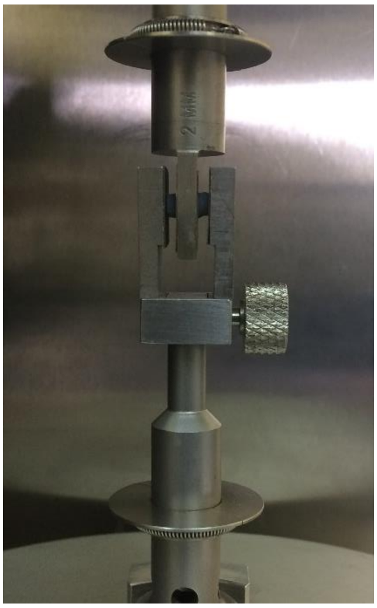
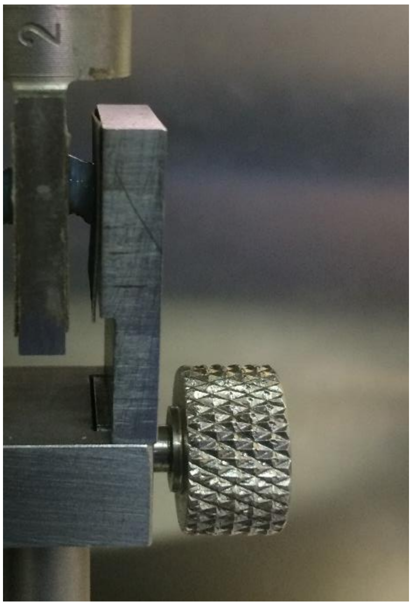


Figure 2. Specimens inside the test tool before test (left) and detail of a specimen after strain was applied (right).

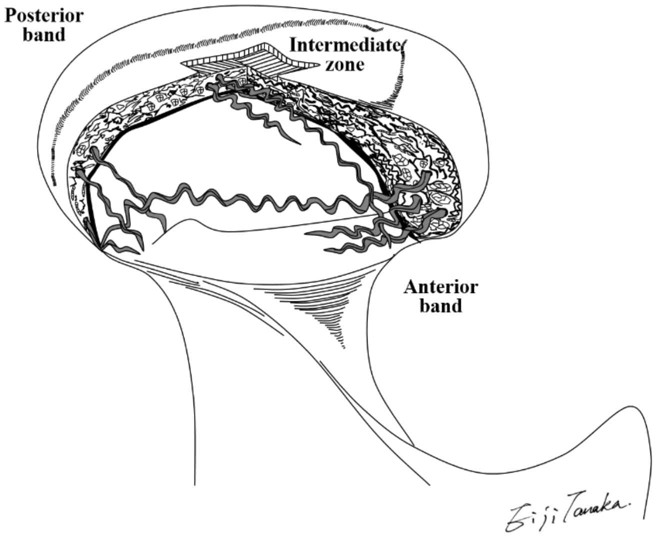


(left)

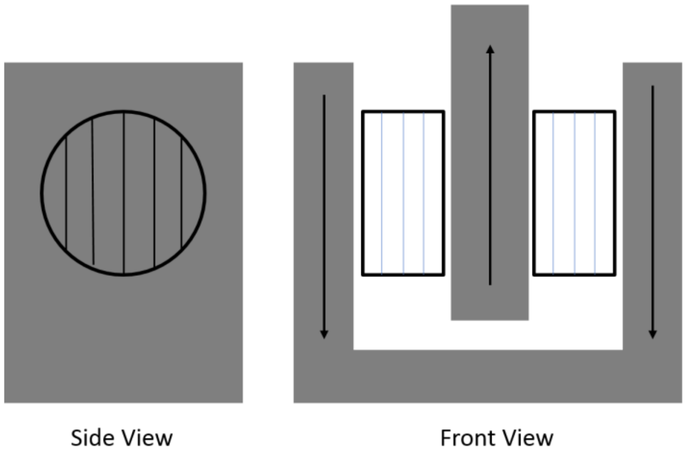


(right)

Figure 3. Fiber distribution of discs (left) and direction of fibers in the tool during antero-posterior testing (right).

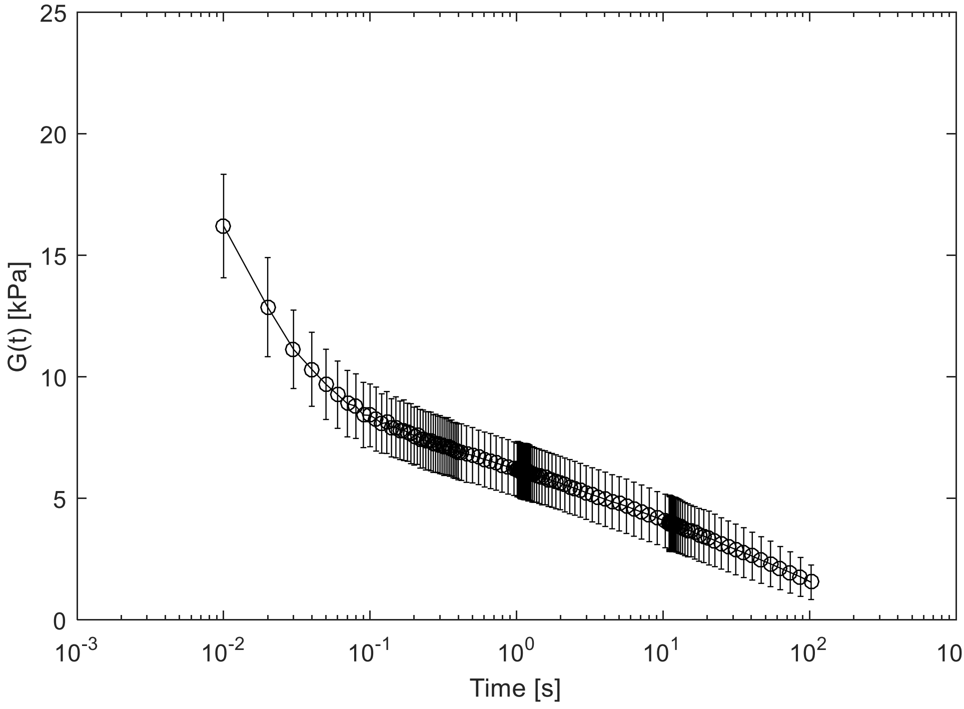


(left)

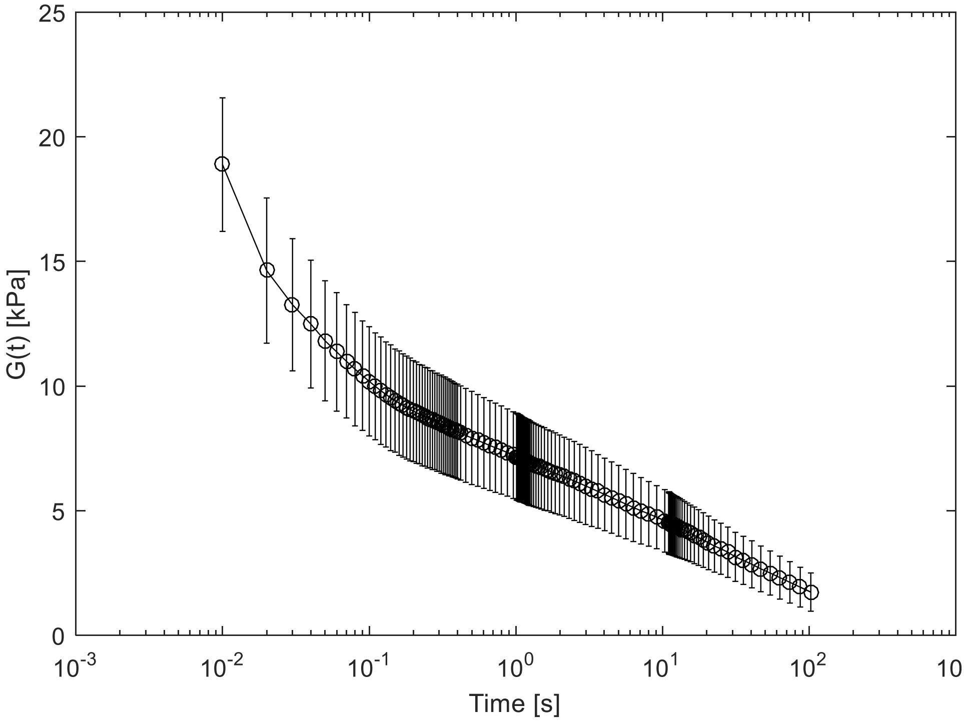


(right)

Figure 4. Shear relaxation modulus for the TMJ disc at $\varepsilon = 5\%$ (left) and $\varepsilon = 8\%$ (right).



(left plot)



(right plot)

Figure 5. Average shear relaxation modulus for the TMJ.

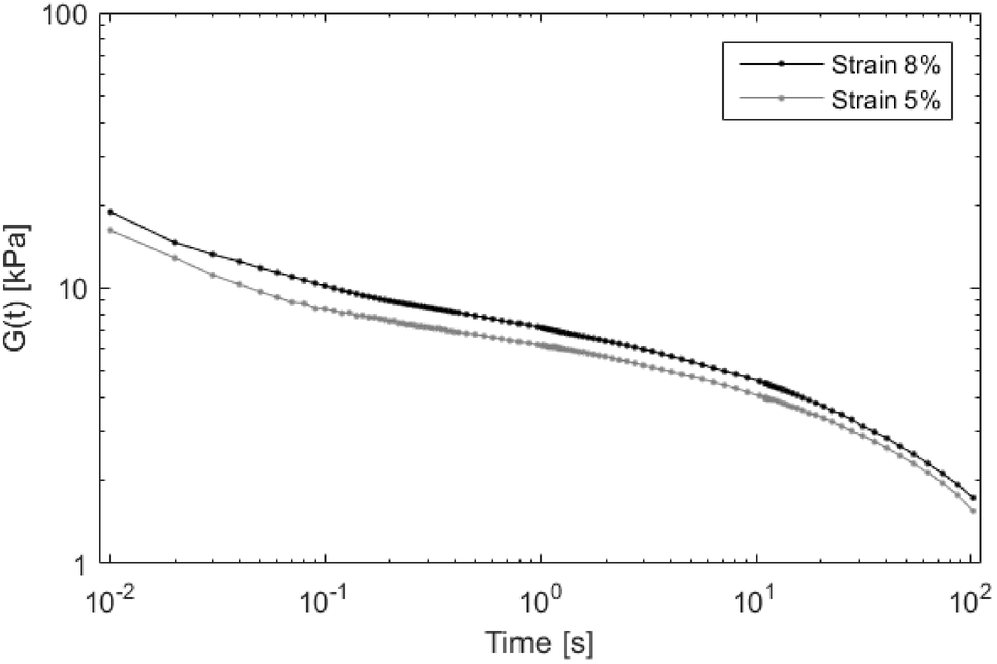


Figure 6. Representation of the generalized Maxwell model.

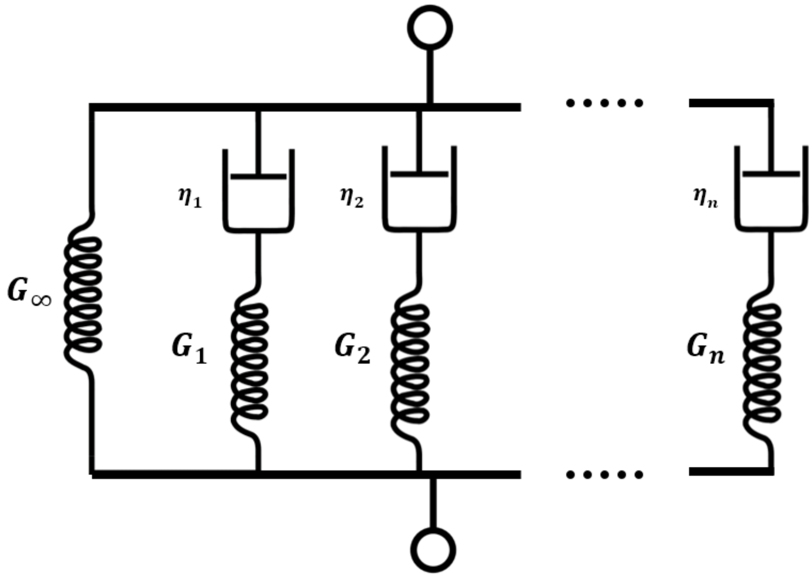
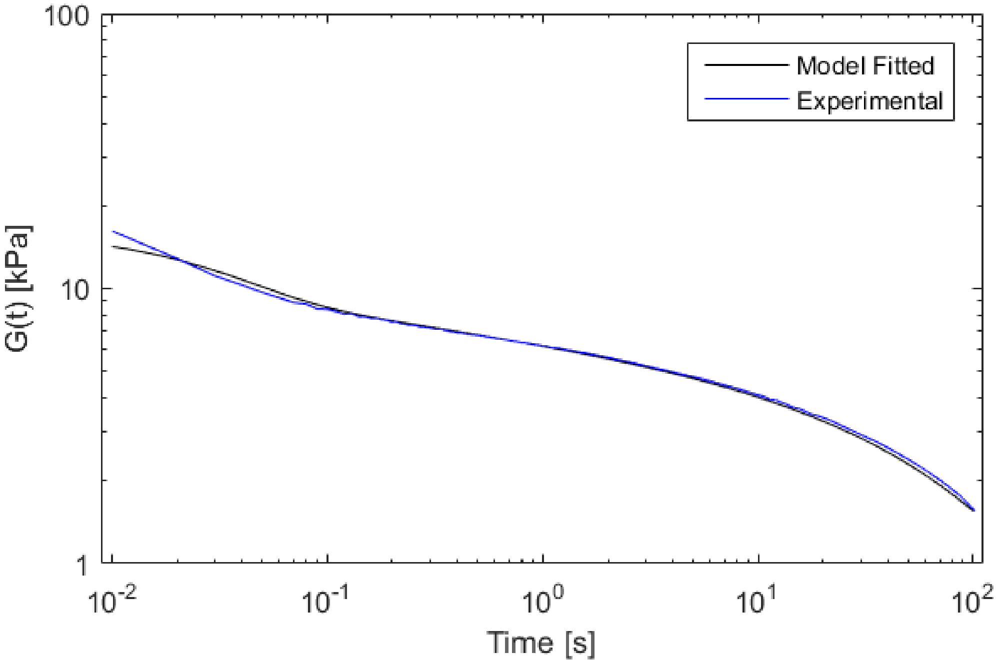
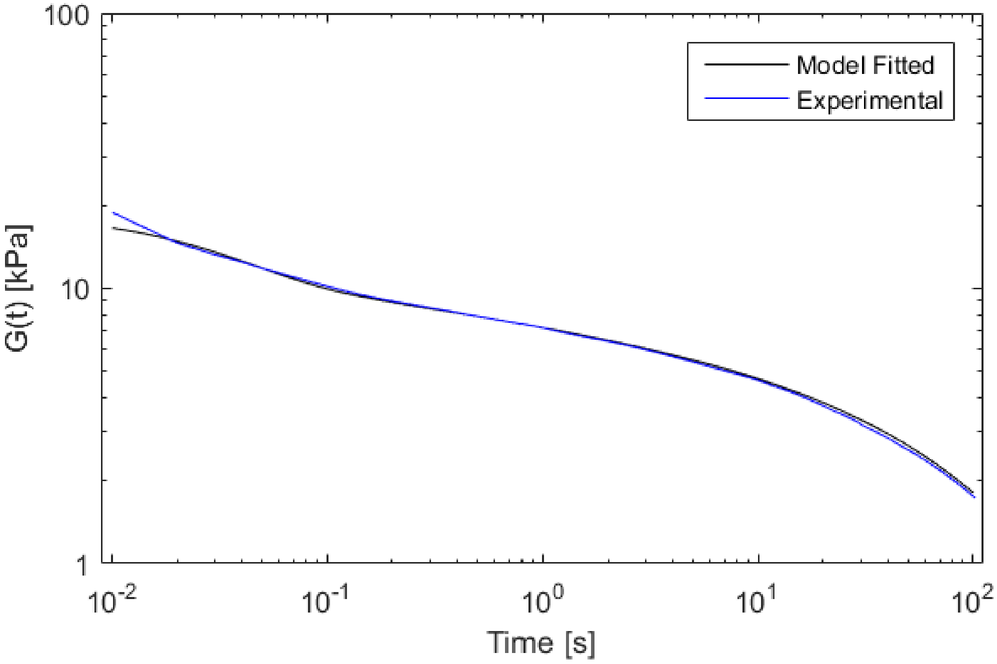


Figure 7. Experimental and analytical (using Eq. (1)) curves for the TMJ shear modulus for 5% (left) and 8% (right).



Level 5% (left)



Level 8% (right)

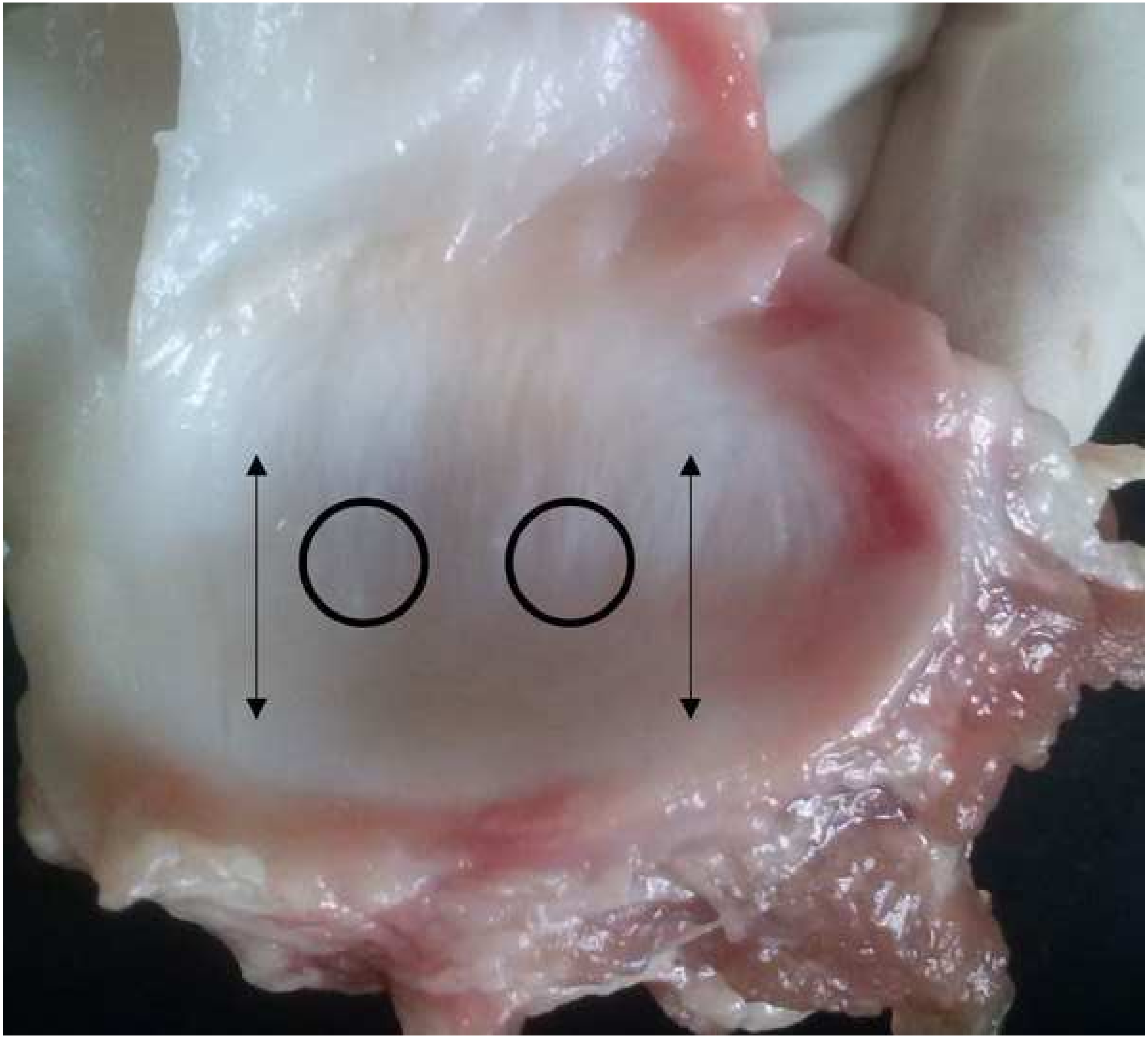
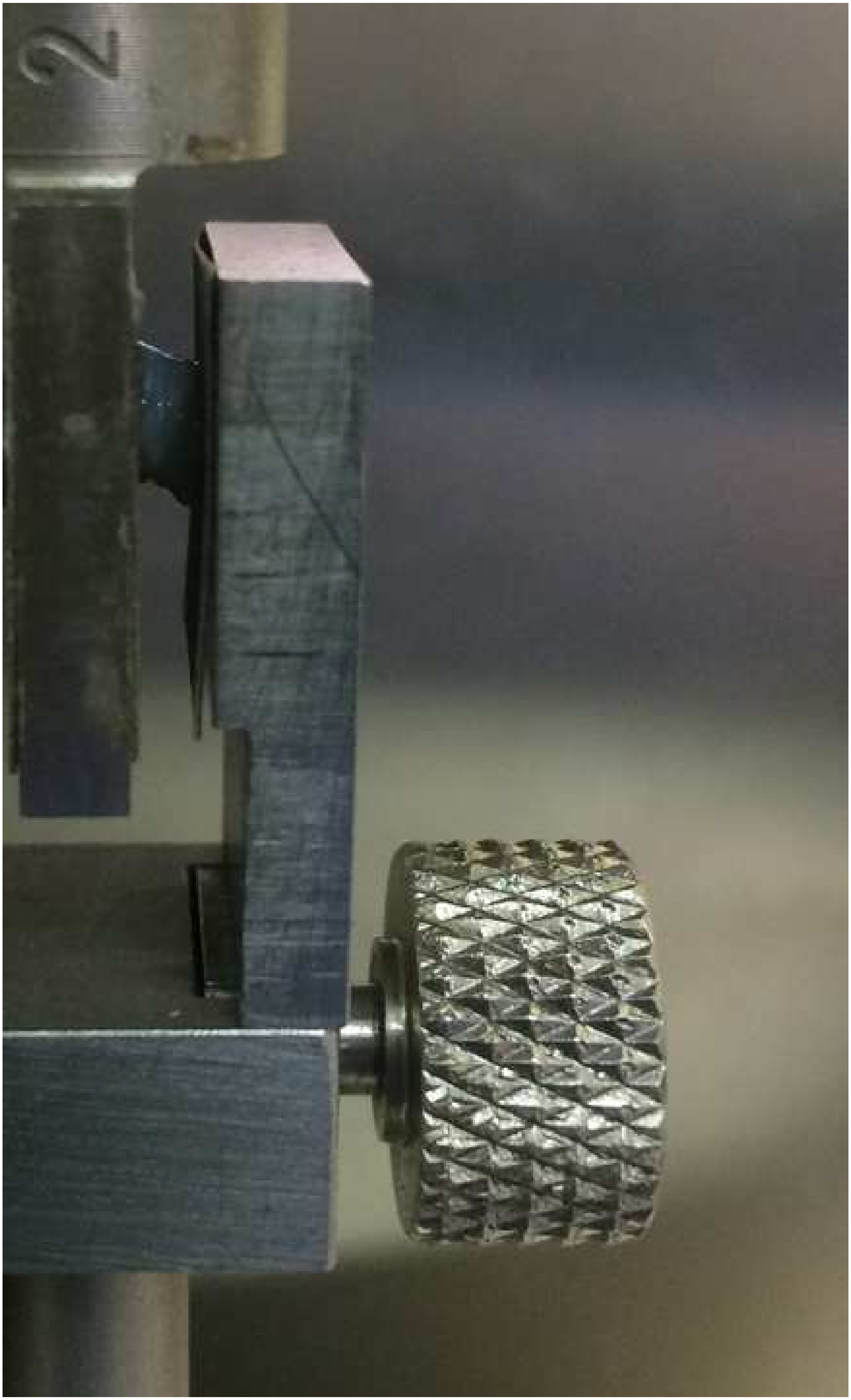
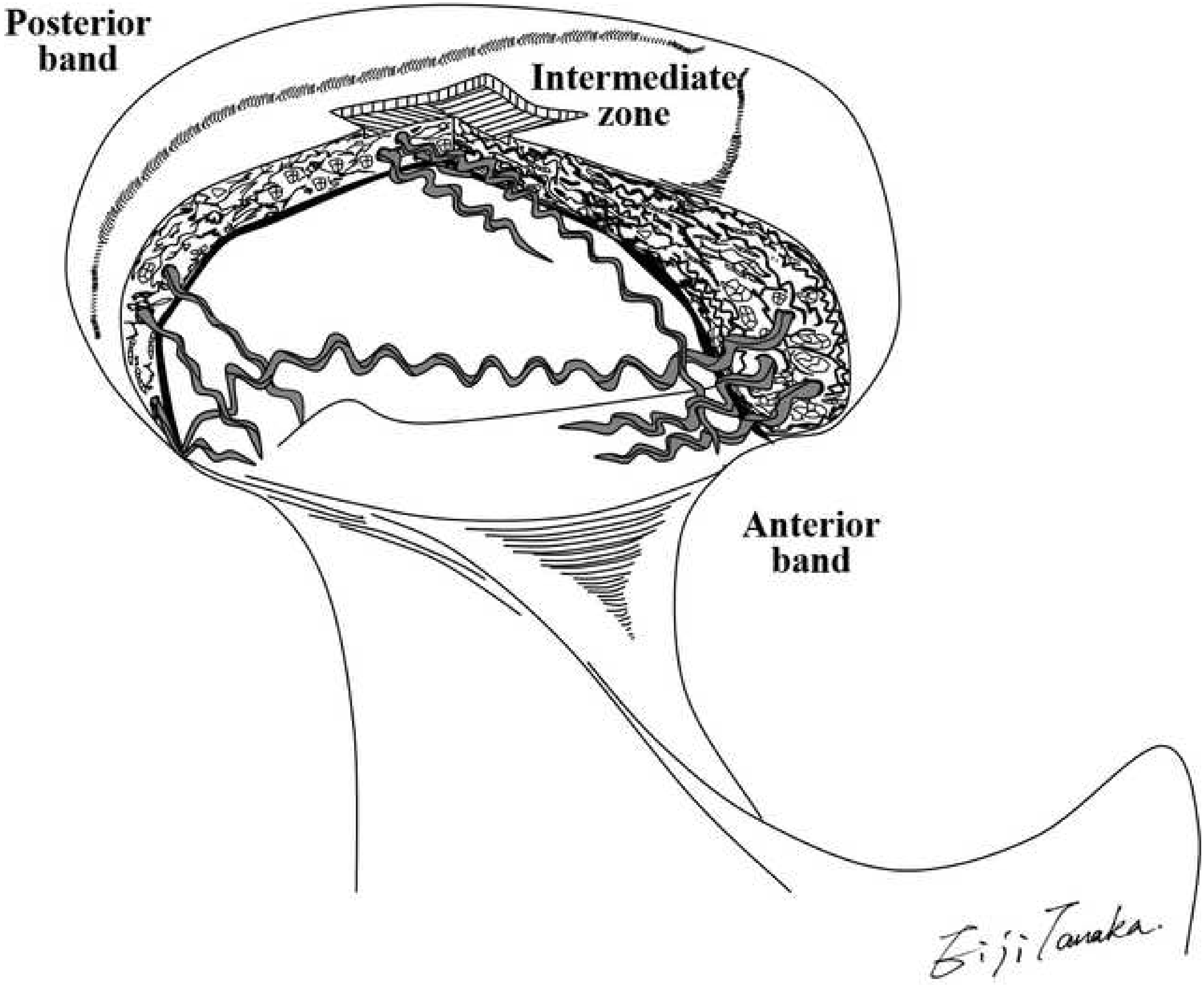
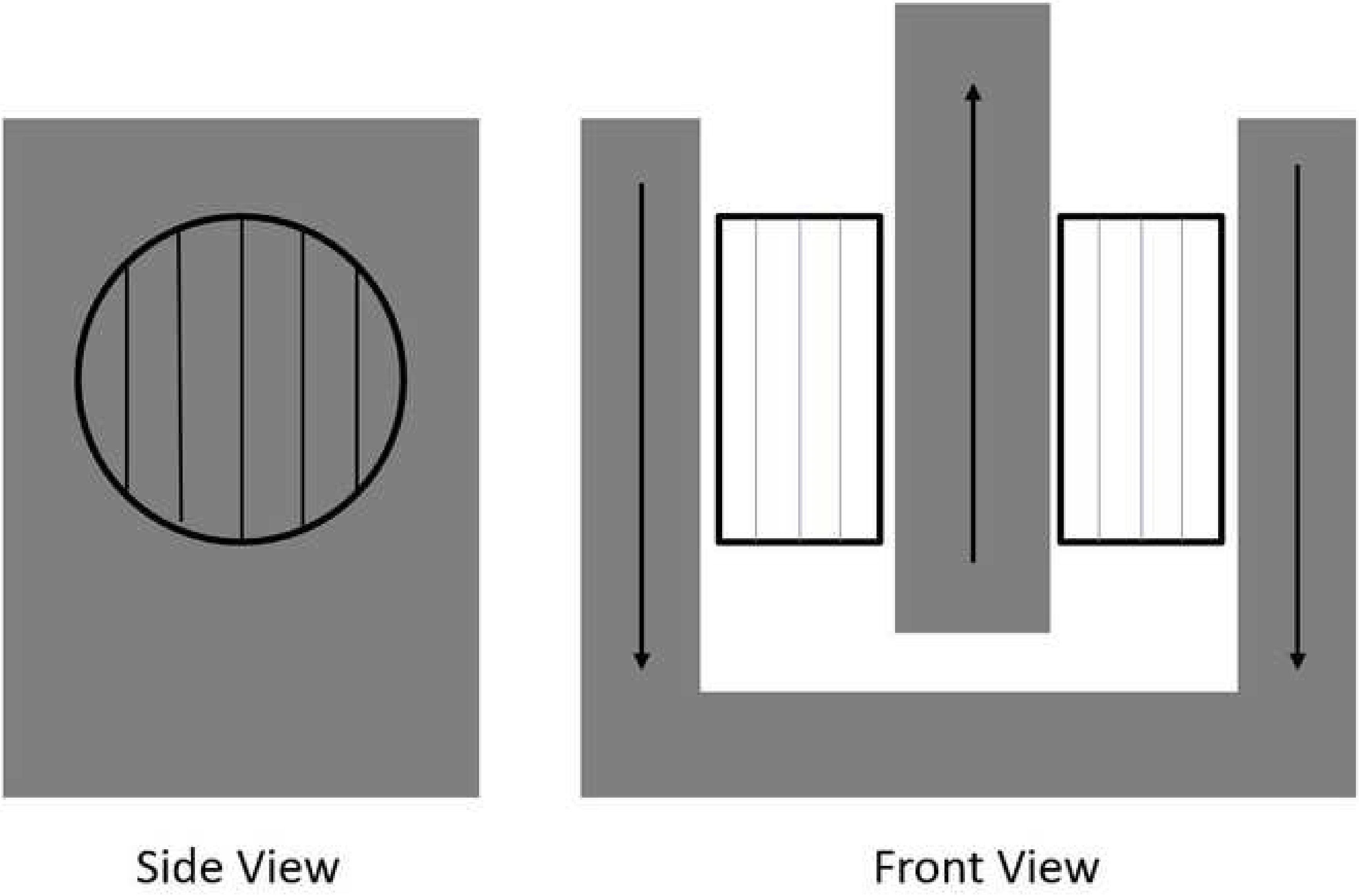


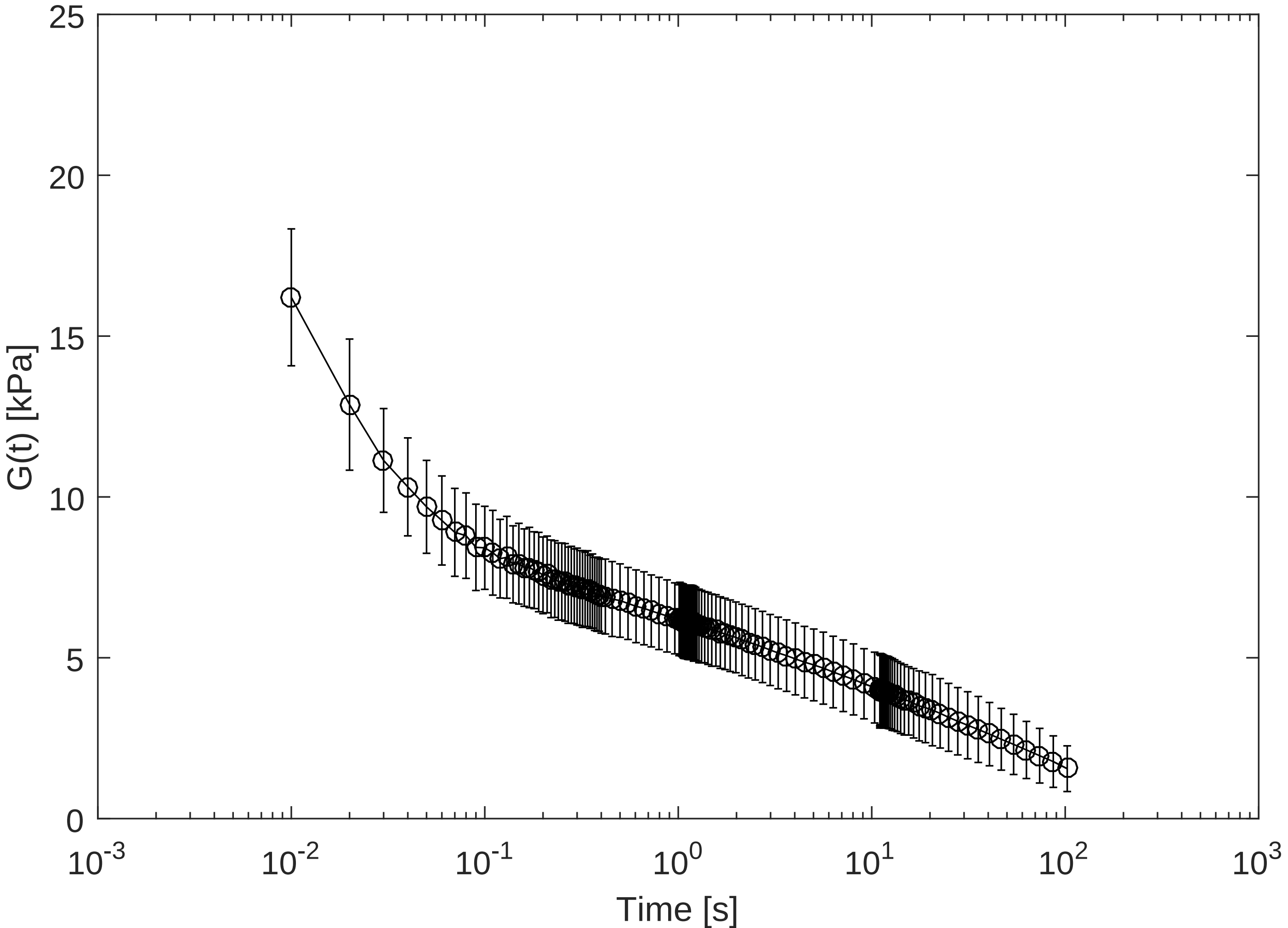
Figure2left

Figure2right

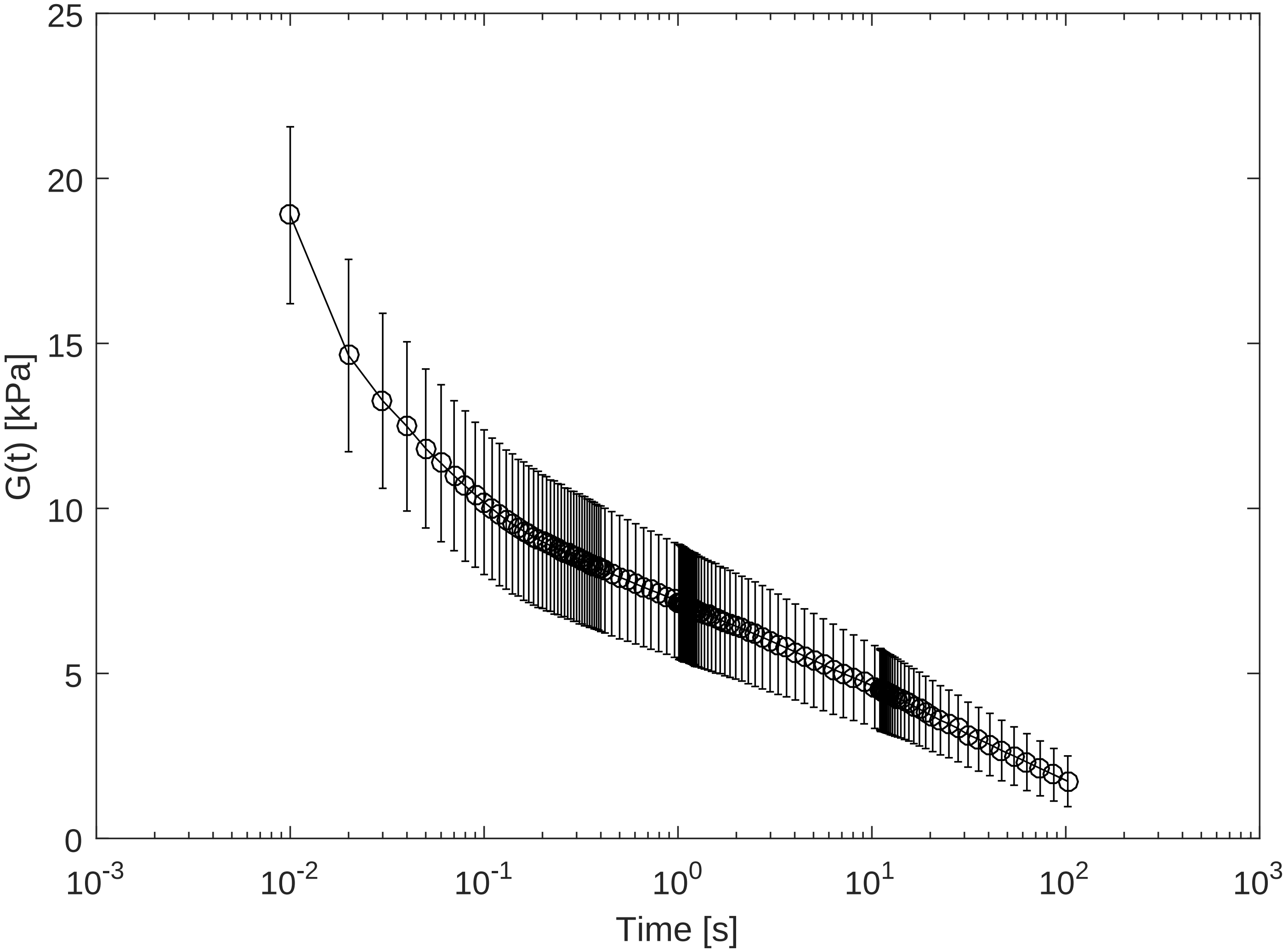


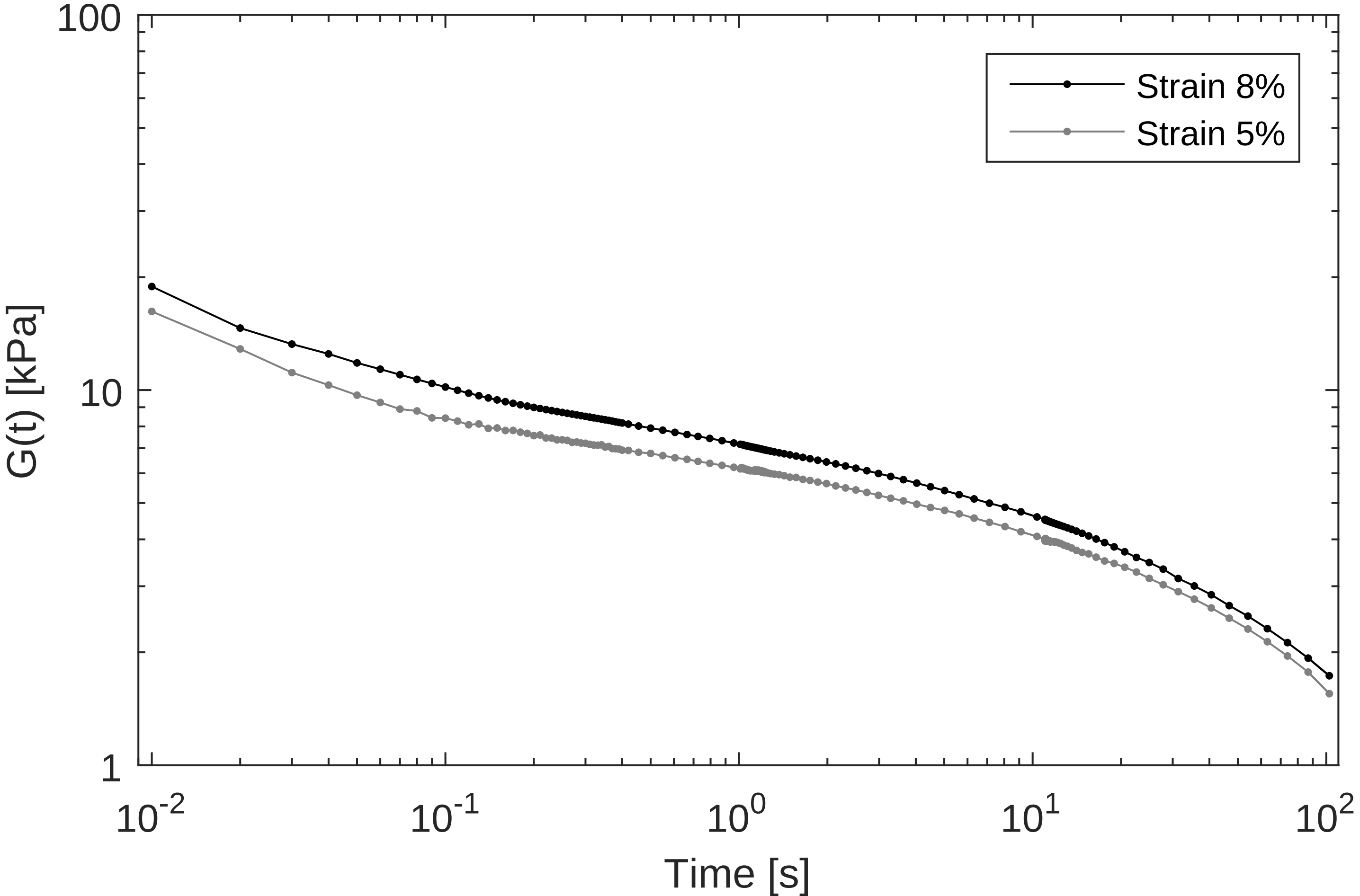

Posterior band
Intermediate zone
Anterior band
Eiji Tanaka.

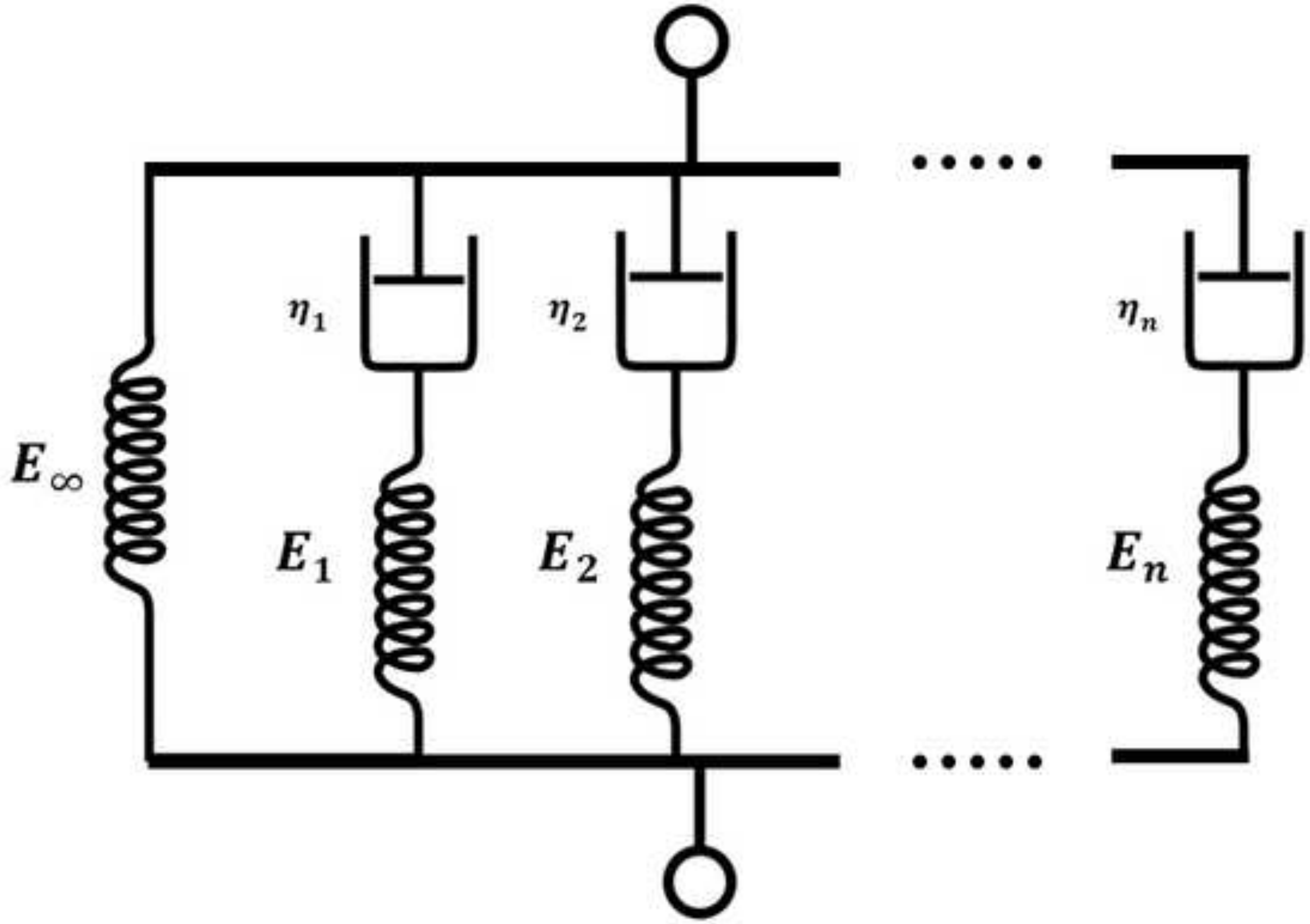

Side View
Front View

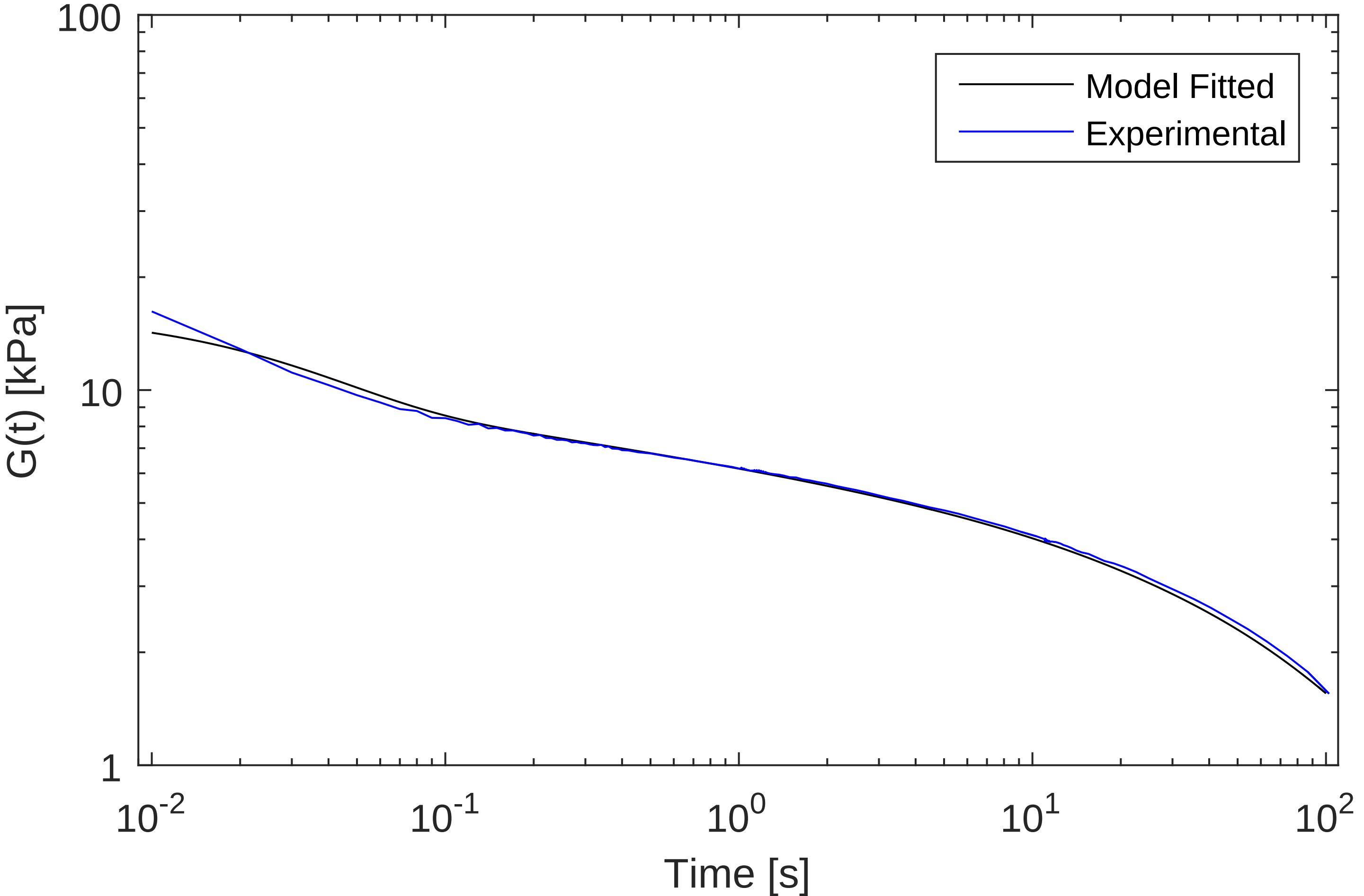


25
20
15
10
5
0
G(t) [kPa]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Time [s]


G(t) [kPa]
25
20
15
10
5
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Time [s]


100
10
1
G(t) [kPa]
10^-2
10^-1
10^0
10^1
10^2
Time [s]
Strain 8%
Strain 5%


E_∞
η_1
E_1
η_2
E_2
η_n
E_n


100
10
1
G(t) [kPa]
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Time [s]
Model Fitted
Experimental

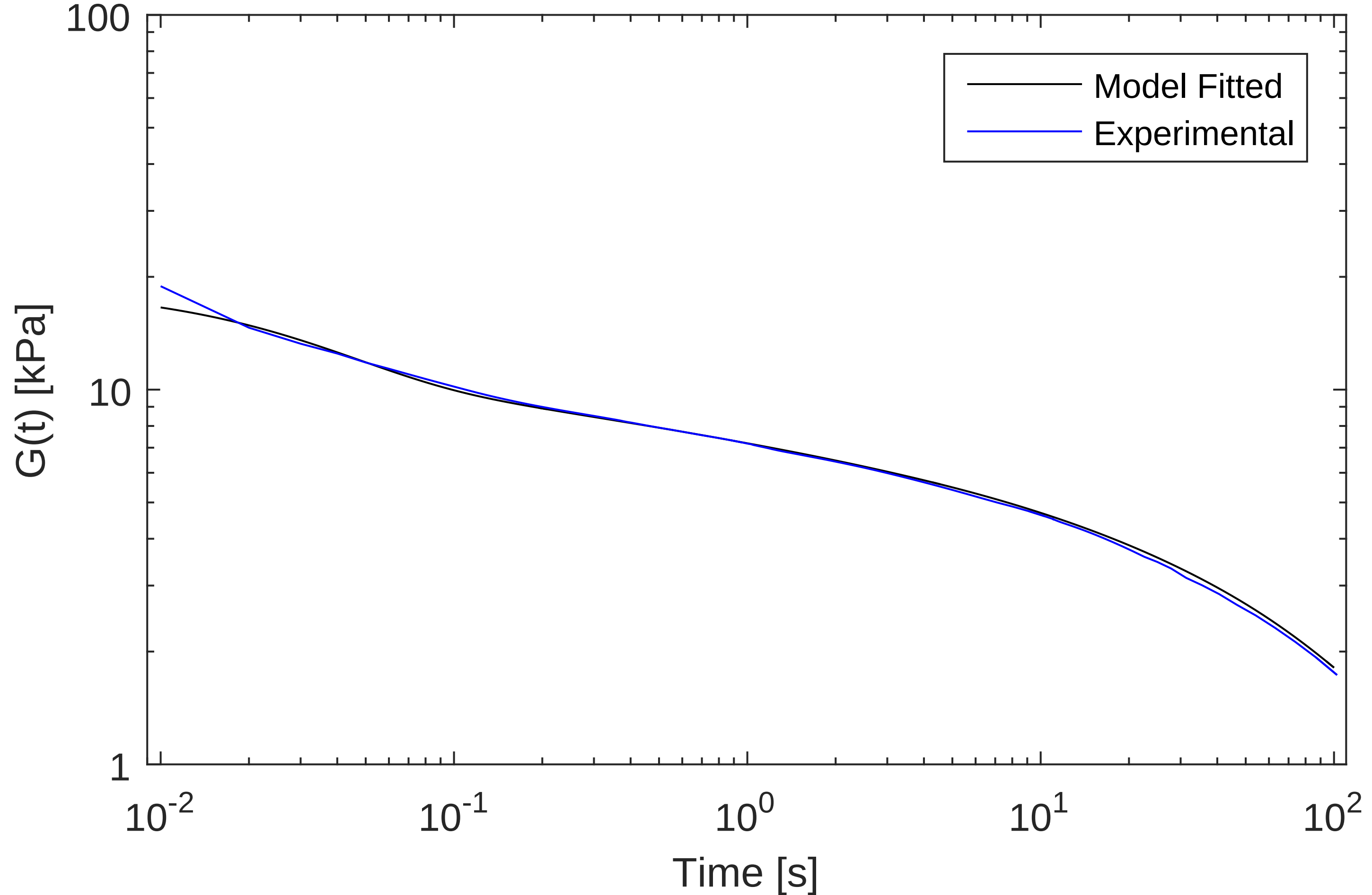

100
10
1
G(t) [kPa]
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Time [s]
Model Fitted
Experimental

Table1

τ_i	G_i
3.17e-02	4.14e-01
1.00e-01	7.90e-02
3.19e-01	6.26e-02
1.01e+00	6.36e-02
3.21e+00	5.68e-02
1.01e+01	7.36e-02
3.22e+01	6.65e-02
1.02e+02	1.44e-01

Table1 appendix

τ_i	G_i
3.171801782714793e-02	4.146791885739055e-01
1.006032675003927e-01	7.901525169602446e-02
3.190936295865514e-01	6.262266247153189e-02
1.012101763417593e+00	6.369962544203969e-02
3.210186241700431e+00	5.687840666168365e-02
1.018207464791342e+01	7.366328040806444e-02
3.229552316589736e+01	6.652140489569733e-02
1.024350000000000e+02	1.443664636944322e-01

Viscoelastic properties of the central region of porcine temporomandibular joint disc in shear stress-relaxation.

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Abstract

In this study, shear relaxation properties of the porcine temporomandibular joint (TMJ) disc are investigated. Previous studies have shown that, in fatigue failure and damage of cartilage and fibrocartilage, shear loads could be one of the biggest contributors to the failure. The aim of the present study is to develop an evaluation method to study shear properties of the disc and to do a mathematical characterization of it. For the experiments, twelve porcine discs were used. Each disc was dissected from the TMJ and, then, static strain control tests were carried out to obtain the shear relaxation modulus for the central region of the discs. From the results, it was found that the disc presents a viscoelastic behavior under shear loads. Relaxation modulus decreased with time. Shear relaxation was 10% of the instantaneous stress, which implies that the viscous properties of the disc cannot be neglected. The present results lead to a better understanding of the discs mechanical behavior under realistic TMJ working conditions.

Keywords: Temporomandibular Joint; Soft Tissues; Viscoelasticity; Biomechanical Characterization; Experimental Techniques; Shear.

1. Introduction

Synovial joints allow various degrees of relative motion among the bones to be regulated by muscles attached to the latter (Widegren et al., 2000). Daily activity accompanies joint motion resulting in joint loads. The temporomandibular joint (TMJ), a diarthrodial synovial joint, enables large relative movements between the temporal bone and the mandibular condyle (Rees, 1954; Scapino et al., 2006). Within the joint, both the articular surfaces of the condyle and temporal bone are covered by a thin fibro-cartilaginous layer showing a very low coefficient of friction (Tanaka et al., 2004b). A dense fibrocartilaginous articular disc is located between the bones in each TMJ. The disc provides a largely passive movable articular surface accommodating the traslatory movement made by the condyle (Koolstra and Tanaka, 2009).

The TMJ disc has an important load-bearing, stress absorbing and joint stabilizing function (Barrientos et al., 2016; Fernández et al., 2013; Tanaka et al., 2008; Tanaka and Eijden, 2003). The disc is subject to various types of loading, such as sustained loading during clenching and intermittent loading during mastication (Hattori-Hara et al., 2014; Hirose et al., 2006; Tanaka et al., 2007). Stresses are divided into compression, tension and shear components. During every type of loading the disc undergoes a deformation while internal forces arise within the tissue. The viscoelasticity of such a material, as that of the disc, is the principal factor of energy dissipation (Fung, 1969). These types of tissues show different mechanism of energy dissipation that are result of the different phases in their structure: interstitial fluid flow within and through the matrix and relaxation of the solid matrix (collagen fibers and proteoglycans). Without strain energy dissipation, storage of the exceeding strain energy can lead to breakage of the articular disc and other components of the TMJ (Tanaka et al., 1999).

Since shear stress can result in fatigue, damage and deformation of cartilage, investigation of shear properties in synovial joints is of particular interest (Spirt et al., 2005; Zhu et al., 1993, 1994). Gallo et al. (2000) suggest that, during mastication, fatigue failure of the TMJ disc could result from shear stresses caused by medio-lateral translation of stress location. Therefore, data on the shear modulus might contribute to a better understanding of secondary tissue damage, such as perforation or thinning of the disc due to long-term exposure to severe loadings. It has been reported that the shear stress in cartilage is very sensitive to the frequency and direction of the loading and to the amount of compressive strain (Mow et al., 1992). However, in the literature few studies are available in which the viscoelastic properties of the TMJ disc are measured in shear stress-relaxation.

This paper may provide better insight about the possible mechanism leading to tissue fatigue and failure due to shear. Therefore, in this study the viscoelastic properties of porcine TMJ disc are investigated under shear stress relaxation, aiming at advancing in the design of biomimetic disc substitutes and in the understanding of the pathological conditions of the TMJ disc.

2. Materials and Methods

In this study, twelve healthy-looking TMJ discs from 6 pigs (age: approx. 6–7 months, gender not specified) were obtained at a local slaughterhouse (Noreña, Asturias, Spain). The protocol of the experiment was approved by the Animal Care and Use Committee at the University of Oviedo, Spain. The discs were carefully dissected immediately after the sacrifice, introduced in hermetic containers immersed in a physiologic saline solution (NaCl 0.09 g/100 ml), and frozen at -25 ºC for 3 days until the experiment was initiated for testing (Allen and Athanasiou, 2005; Calvo-Gallego et al., 2017). The discs were completely unfrozen in a refrigerator at 3-4 ºC and, then, allow to reach room temperature (20 ºC) before testing. Using a cylindrical 4.0 mm diameter tissue punch, two experimental specimens were dissected from the central region of each disc (see Figure 1).

Although previous studies have shown region-dependent mechanical properties (Fernández et al., 2013), this study is only focused on the central region, mainly due to the complexity of extracting two specimens with the necessary dimensions of the rest of regions.

All the specimens were tested in a DMA Instrument (RSA3, T.A. Instruments, USA) in unconfined shear using a shear tool (see Figure 2) at room temperature (20 ºC). The loading was applied in the antero-posterior direction, since mechanical properties of the disc, due to fiber distribution, will also be direction-dependent.

As mentioned before, two specimens of each disc were cut. In Figure 2, it can be seen that the shear-tool has a sandwich configuration and samples need to be placed at both sides of the tool. In order to test shear in antero-posterior direction, the fibers of the specimens need to be aligned with the movement of the tool (vertical direction), according to Figure 3.

To avoid the specimens' slippage during shear loading, 600 grit sandpaper was glued to the surfaces of the shear tool. Additionally, the selected inner part of the shear tool would allow testing 2 mm thick specimens. Taking into account the average thickness value for the discs, 1.84±0.11 mm, and the real gap for testing, 1.750 mm (subtracting the sandpaper sheet thickness), an average initial value of 5% pre-strain in the compression direction was applied before testing. After previous step, a 3-min preconditioning test was performed with 1% sinusoidal strain before the subsequent shear stress relaxation test. The shear strain was applied to the specimens moving the lower part of the tool in the axial direction of the machine (vertical direction in Figure 2 and 3). Shear strain levels of the TMJ disc produced under ordinary mandibular movement have not been reported. Previous studies do not show consensus for shear strain (Lai et al., 1998; Tanaka et al., 2004a). Due to the limitations of testing the specimens under shear conditions, i.e. very low loads for strain values lower than 5% or problems of slippage for strain values larger than 10%, tests were carried out at strain levels of 5% and 8% in order to obtain the corresponding relaxation modulus.

The specific level of shear strain was produced under an instantaneous strain step and kept constant during 120 seconds for each stress relaxation test keeping the same test procedure used in previous studies (Barrientos et al., 2016).

To apply and maintain the initial value of strain during the relaxation test, the DMTA machine is equipped with a motor driven by an air bearing system, which applies the corresponding displacement at a very high rate once the strain is commanded before testing (T.A.Instruments, 2001). Loads were measured simultaneously under the specified constant strain.

3. Results

3.1 Viscoelastic properties of porcine TMJ disc in shear stress relaxation

From the experimental tests, the mean and standard deviation of the shear modulus of the TMJ disc at convenient times were calculated. The resulting curves for the 5 and 8 % strain levels are presented in Figure 4 (left and right plots, respectively).

For comparison proposals both averaged curves are plotted in Figure 5. From Figure 5, a higher shear modulus is observed for the 8 % strain level. From the results (Figure 5), a dependence of the relaxation modulus, $G(t)$, with applied strain can be observed, which is in agreement with the TMJ disc behaviour previously observed (Lamela et al., 2011).

The shear modulus obtained for both strain levels (see Figure 5) presents a large relaxation ratio. For 1 s, the shear modulus decreases about 70% while a 90 % reduction is observed for 100 s.

3.2 TMJ shear relaxation model

Due to its simplicity, even though other models could be used, generalized Maxwell model was used to fit the experimental data to the viscoelastic model represented in Figure 6, as a combination of spring and dashpot elements (Tschoegl, 2012), which can be modelled using the Prony´s series model given by the equation:

$$\mathrm{G(t)} = \mathrm{G_0}\left[1 - \sum_{\mathrm{i=1}}^{\mathrm{n_t}} \mathrm{g_i}\left(1 - \exp\left(-\frac{\mathrm{t}}{\mathrm{\tau_i}}\right)\right)\right] \tag{1}$$

where g_i and τ_i are the Prony parameters and G_0 is the instantaneous shear modulus.

To simplify the material model, as well as to take into account the dependence of the $G(t)$ with the applied strain, a unique set of Prony parameters was used to fit both shear modulus curves. This procedure profits from the fact that a simple vertical shift is observed between both material curves (see Figure 5) which could be interpreted as a proportional shift of $G(t)$ with the strain.

Two steps were used for fitting the material model. Firstly, the shear curves for the TMJ are averaged and, next, the generalized Maxwell model was applied to fit the averaged curve by means of the Prony series equation (1).

To fit adequately the experimental data, 8 Prony terms were necessary being the R-square 0.994. The parameters of the Prony series presented in Table 1 define the normalized viscoelastic curve for the material, as a function of the instantaneous modulus of the material, G_0. In this way, the curves for the 5% and the 8% strains are gained from the fitted model, simply, by multiplying in each case equation (1), by the corresponding instantaneous modulus. Accordingly, $\mathrm{G}_0^{5\%} = 1.6205\mathrm{e}+04$ kPa and $\mathrm{G}_0^{8\%} = 1.8883\mathrm{e}+04$ kPa, for the 5 % and the 8 % shear modulus curves, respectively. The Prony series parameters with higher precision are included in the appendix.

Table 1. Prony series parameters (R^2=0.994) for the normalized TMJ shear modulus curve.

τ_i	G_i
3.17e-02	4.14e-01
1.00e-01	7.90e-02
3.19e-01	6.26e-02
1.01e+00	6.36e-02
3.21e+00	5.68e-02
1.01e+01	7.36e-02
3.22e+01	6.65e-02
1.02e+02	1.44e-01

The experimental and the analytical curves (using equation (1)) are presented in Figure 7**.** The maximum error between the experimental results and the proposed model are less than a 2% for both curves.

4. Discussion

Fatigue failure and damage of joint tissues, including both disc and cartilage, may be more linked to repeated and prolonged extension and shear motions than to the joint compression applied (Iatridis and ap Gwynn, 2004; Tanaka et al., 2003). Even when the disc slides along smooth temporal cartilage during jaw movements, shear loading of the disc and cartilage has been considered to be negligible due to almost zero friction. However, several authors support the evidence that the disc and cartilage are subjected to shear stress. For example, after prolonged clenching and grinding, only solid contact may exist between the disc and cartilages, without boundary lubrication between them, resulting in considerable shear stress (Forster and Fisher, 1999, 1996; Tanaka et al., 2001). Few studies of the behaviour of the TMJ disc under dynamic shear loads were performed in the past (Juran et al., 2013; Koolstra et al., 2007; Tanaka et al., 2004a, 2003) to evaluate the mechanical properties of the disc at different strain rates and frequencies. The present study is, as far as we know, the first, in which the shear relaxation properties of the TMJ disc in shear stress relaxation were examined. Wu et al. (2015) investigated the intrinsic viscoelastic shear properties in porcine TMJ disc, but in contrast to the present study, they applied a rotational shear loading. The present design might reproduce the actual environment in the TMJ disc. Previous studies have shown that due to morphology, function and diet, pig discs are the closest to human discs making them an appropriate model for TMJ studies (Bermejo et al., 1993; Kalpakci et al., 2011). In this study, relaxation viscoelastic behaviour of cut porcine specimens is evaluated in antero-posterior direction at 5 and 8% shear strain levels. As a result, the instantaneous shear moduli were increased with increasing applied strain. This evidences a dependence with strain of the behaviour of the disc which is in good agreement with the general mechanical behaviour observed previously in the TMJ disc (Lamela et al., 2011; Tanaka and Eijden, 2003).The possible explanation for this increment is the stretching of collagen fibers in antero-posterior direction (Barrientos et al., 2016; Lamela et al., 2011; Tanaka et al., 2003). Furthermore, present results show that the relaxed stress of the porcine TMJ disc was approximately 10% of the instantaneous stress irrespective of shear strain amplitude. This indicates that energy-dissipation function takes place in the TMJ disc. Without the energy dissipation capacity of the disc, TMJ components including bony components and soft tissue probably fail resulting in the tissue rupture. Thus far, it is concluded that the TMJ disc plays an important role as a stress bumper during complex mandibular movements.

When comparing the compression relaxation tests (Barrientos et al., 2016; Lamela et al., 2011) with the shear relaxation tests, the present results clearly show that compression relaxation modulus is 10 times higher than shear relaxation modulus. Adam et al. (2015) investigated an image-based modelling study on the bovine caudal disc, and concluded that shear resistance between lamellae confers disc mechanical resistance to compression. This points out the relationship between shear and compressive properties of the TMJ disc. Moreover, the present results reveal that the porcine TMJ discs exhibited shorter relaxation times under shear stress relaxation than under compressive stress relaxation. This may be due to the difference of an outflow of interstitial fluid caused by pressurization of the compressed area. During shear stress relaxation, the fluid within the disc is likely to move along the stretching collagen fibers; however, during compressive stress relaxation, the disc maintains a fluid pressure because of sustained interstitial fluids within the disc. Since the load bearing functions of cartilaginous tissues are mainly provided by the viscoelastic property of collagen fiber network and the osmotic pressure due to the presence of proteoglycans (Hardingham and Fosang, 1992), the large proteoglycans and the related chondroitin sulfate might be more important to counteract compression and shear, while the collagen fibers are more important to counteract tension (Tanaka and Eijden, 2003).

Mow et al., (1980) reported about the biphasic theory, this theory is suitable for better understanding of the mechanisms involved in energy dissipation. Due to the highly heterogeneous structure of the TMJ disc, the viscoelastic approach used in this study gives a global understanding of the mechanical properties of the disc rather than the material constitutive law.

In literature, authors have used different models to characterize the viscoelastic properties of the TMJ disc (Allen and Athanasiou, 2006; Tanaka and Eijden, 2003). For large displacements, other models could be more appropriate (Fung, 1969). In this study, a generalized Maxwell model, based on Prony´s series, was applied to characterize the shear relaxation modulus of the material. Although the TMJ disc presents a strain-dependent behavior, almost the same relaxation rate is observed for the strain levels applied in the experiments (see Figure 5). This fact allows a unique viscoelastic model to be fitted where the instantaneous modulus, G_0, at the corresponding strain level must be used. The results obtained with the proposed Prony series model can be considered adequate for the shear relaxation modulus of the TMJ disc showing errors under 2%.

To be consistent with previous studies and allowed comparison (Barrientos et al., 2016; Fernández et al., 2013), some testing conditions, such relaxation time and temperature, and model parameters were chosen. Temperature affects mechanical results as higher temperatures reduce stiffness and strength of the discs (Detamore and Athanasiou, 2003).

In conclusion, the relaxation properties of the porcine disc were determined under shear in this study. A new methodology to test the disc under relaxation shear conditions was proposed. The study shows that the viscoelastic properties of the disc under shear loads cannot be neglected. Shear properties of the disc in antero-posterior direction were characterized using a unique Maxwell model. Nevertheless, this study is a first step in the shear characterization of the TMJ discs and further studies are needed to conclude on the shear behavior of the disc in medio-lateral direction, cyclic loads, pre-compression and region dependencies.

5. Acknowledgments

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7. Appendix A

Table 1. Prony Series coefficients for the TMJ Shear modulus with higher precision

τ_i	G_i
3.171801782714793e-02	4.146791885739055e-01
1.006032675003927e-01	7.901525169602446e-02
3.190936295865514e-01	6.262266247153189e-02
1.012101763417593e+00	6.369962544203969e-02
3.210186241700431e+00	5.687840666168365e-02
1.018207464791342e+01	7.366328040806444e-02
3.229552316589736e+01	6.652140489569733e-02
1.024350000000000e+02	1.443664636944322e-01