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Short communication

Effect of non-uniform thickness of samples in stress relaxation tests under unconfined compression of samples of articular discs

Maria S. Commisso [a,*], Javier Martínez-Reina [a], Juana Mayo [a], Jaime Domínguez [a], Eiji Tanaka [b]

[a] Department of Mechanical Engineering, University of Seville, Camino de los Descubrimientos s/n, E-41092 Seville, Spain
[b] Department of Orthodontics and Dentofacial Orthopedics, The University of Tokushima Graduate School, Tokushima, Japan

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ABSTRACT

A precise information of the biomechanical properties of soft tissues is required to develop a suitable simulation model, with which the distribution of stress and strain in the complex structures can be estimated. Many soft tissues have been mechanically characterized by stress relaxation tests under unconfined or confined compression. In general, full-thickness samples are extracted to reduce the damage in the tissue as much as possible. However, it is not guaranteed that these samples have a uniform thickness or, in other words, planar parallel faces. In particular, in the articular disc of the temporomandibular joint, many studies can be found testing full-thickness samples for which that thickness is known to be non-uniform, while making the assumption of uniaxial stress state to extract the mechanical properties from those tests. That inaccuracy may have a strong influence in some cases and needs a profound revision. The main goal of this work is to quantify the error committed in that assumption and the influence of the variation of thickness on that error in a particular test: stress relaxation tests under unconfined compression. Based on this error and defining an allowable tolerance, a criterion is established to reject samples depending on their aspect ratio.

1. Introduction

Stress-relaxation tests in unconfined or confined compression are usually performed in soft tissues to characterize their viscoelastic properties (Loocke et al., 2008; Miller-Young et al., 2002; Hatami-Marbini and Etebu, 2013; Julkunen et al., 2008; Tanaka et al., 1999; Allen and Athanasiou, 2006). In general, the sample preparation consists in extracting a cylindrical piece from the sample with a tissue punch (Julkunen et al., 2008; Miller-Young et al., 2002; Allen and Athanasiou, 2006; Lamela et al., 2011). When cylindrical samples are tested, their faces should be parallel to ensure a uniaxial stress state. In some works, the specimens are also cut in its thickness to obtain parallel faces (Seitz et al., 2013; Allen and Athanasiou, 2006; Miller-Young et al., 2002). However, apart from the damage produced by cutting the sample, getting parallel faces is not assured in most cases (Allen and Athanasiou, 2006).

The thickness of articular discs is highly variable, making it difficult to extract samples with uniform thickness. This fact has been mentioned in several works using articular discs from different animal species where full-thickness samples were tested (Tanaka et al., 1999; Nishimuta and Levenston, 2012; Sweigart et al., 2004) or in cases where the samples were cut in their thickness (Allen and Athanasiou, 2006; Seitz et al., 2013; Leslie et al., 2000). An extra difficulty of articular discs is that its mechanical properties partly depend on the thickness (Detamore and Athanasiou, 2003; Lai and Levenston, 2010). So, cutting the sample induces an additional variable and the exact position of the slice within the thickness, which complicates the experimental characterization of the disc. Furthermore, if the objective is to obtain average properties through the thickness, full-thickness samples are required.

The quasi-linear viscoelastic (QLV) model (Fung, 1993) has been used in a large number of soft tissues (Carew et al., 1999; Drapaca et al., 2006) and was shown to suitably model the mechanical behavior of the articular disc (Commisso, 2012).

Finite element (FE) simulations of the stress-relaxation test have shown that the typical variation of thickness seen in the central part of the articular disc of pigs can produce a stress distribution which is quite far from the uniaxial case and this may lead to an incorrect identification of the viscoelastic constants (Commisso et al., 2013). This observation is well-known and has

* Corresponding author: Tel.: +34 954481365; fax: +34 954460475.
E-mail address: mcommisso1@us.es (M.S. Commisso).

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been reported in the related literature (e.g. Seitz et al., 2013), but it has still been overlooked in many studies testing full-thickness samples. What is not known is how that lack of uniformity affects the material constants fitted from the experimental testing. This influence is addressed in this paper in order to ensure the validity of testing full-thickness samples.

The objective of this paper is to evaluate the influence of the variation of thickness on that error in a stress relaxation test under unconfined compression. Based on this error and defining an allowable tolerance, a criterion is established to reject samples depending on their aspect ratio.

2. Materials and methods

2.1. Geometry of the specimens

The articular disc of the temporomandibular joint (TMJ) is the soft tissue selected for this study. 72 articular discs harvested from *large white pigs* were used. Since it is difficult to extract several samples with a more or less uniform thickness from one disc, a single sample from the central region of each disc was selected, as done by Tanaka et al. (1999). Cylindrical samples with an approximately circular cross sectional area were extracted using three punches of different diameters: 4 mm (D1), 5 mm (D2) and 6 mm (D3). The samples were photographed to measure their area with imaging techniques, so providing an equivalent diameter (ϕ_{eq}), given in Table 1. The thickness of the samples was measured using optic microscopy (Nikon Optiphot XPF-M, 100 ×) at 8 points equally spaced over the periphery plus the middle point of each sample (see dots in Fig. 1). An average of the 9 measurements were made to establish an average thickness (L). The difference between the maximum and minimum thickness measured was used to characterize the variation in thickness, ΔL.

Table 1
Dimensions (mean ± SD) of the cross sectional area, diameter, average thickness and variation in thickness measured in samples of porcine articular discs.

Samples	Area (mm^2)	ϕ_{eq} (mm)	L (mm)	ΔL (mm)
D1	11.71 ± 0.83	3.86 ± 0.14	1.92 ± 0.44	0.34 ± 0.20
D2	17.98 ± 1.81	4.78 ± 0.24	2.14 ± 0.43	0.53 ± 0.28
D3	23.38 ± 3.64	5.43 ± 0.43	1.95 ± 0.44	0.89 ± 0.30

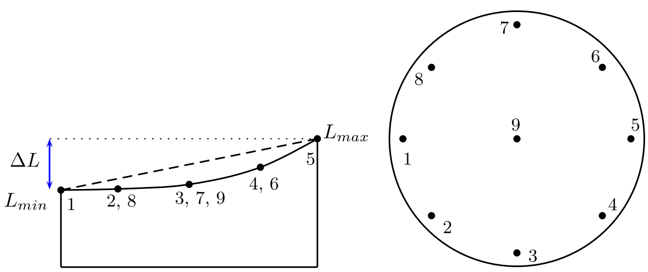

Fig. 1. Schematic geometry of a real sample (solid line). At the left, lateral view and at the right, upper view. In dashed line, simplification made in the finite element model to represent the variation in its thickness. In dots, points where the thickness is measured.

2.2. Material model

The QLV formulation (Fung, 1993) is used to describe the viscoelastic behavior of the articular disc. The stress history is factorized in a reduced relaxation function, $\overline{G}(t)$, and an elastic response, $T^{(e)}(\lambda)$. If the stretch is applied as a step function ($\lambda = \lambda_0 H(t)$, $H(t)$ being the Heaviside function), the stress response is given by the following:

$$\sigma(\lambda, t) = \overline{G}(t) T^{(e)}(\lambda) \quad (1)$$

For a general $\lambda = \lambda(t)$, the stress can be written as (see Commisso et al., 2013 for further details)

$$\sigma(t) = \int_0^t \overline{G}(t-\tau) \frac{dT^e[\lambda(\tau)]}{d\lambda} \frac{d\lambda(\tau)}{d\tau} d\tau \quad (2)$$

A two-term Prony series and an exponential hyperelastic model were chosen to characterize the mechanical response of the articular disc (Commisso et al., 2013). The relaxation function is

$$\overline{G}(t) = g_\infty + g_1 e^{-t/\tau_1} + g_2 e^{-t/\tau_2} \quad (3)$$

where g_1, g_2 and g_∞ are the short-term, mid-term and long-term relaxation coefficients, respectively, while τ_1 and τ_2 are the short-term and mid-term relaxation times. The incompressible elastic response is given by the strain energy function:

$$\psi = A[e^{B(I_1-3)} - 1] \quad (4)$$

where I_1 is the first invariant of the right Cauchy–Green tensor and A and B are material constants. In this case and in uniaxial stress, $T^{(e)}$ is

$$T^{(e)}(\lambda) = 2ABe^{B(\lambda^2 + (2/\lambda) - 3)} \left(\lambda^2 - \frac{1}{\lambda}\right) \quad (5)$$

2.3. FE simulation of the test

Finite element (FE) models were created from the dimensions of real specimens (see Fig. 2). Three diameters: ϕ=3.5, 4.5 and 5.5 mm (considering the change in diameter after the extraction of the samples, see Table 1) and seven average thicknesses ($L \in [1.14, 2.50]$ mm) were used to create the FE models. The samples were meshed with linear 8-noded hybrid hexahedral elements (type C3D8H of the elements library of Abaqus FEA®). The model was simplified to have planar faces (see Fig. 1). Based on the variation of thickness measured (see Table 1), the following cases were analyzed: "E0", where $\Delta L = 0$ mm; "E1", $\Delta L = 0.25$ mm; "E2",

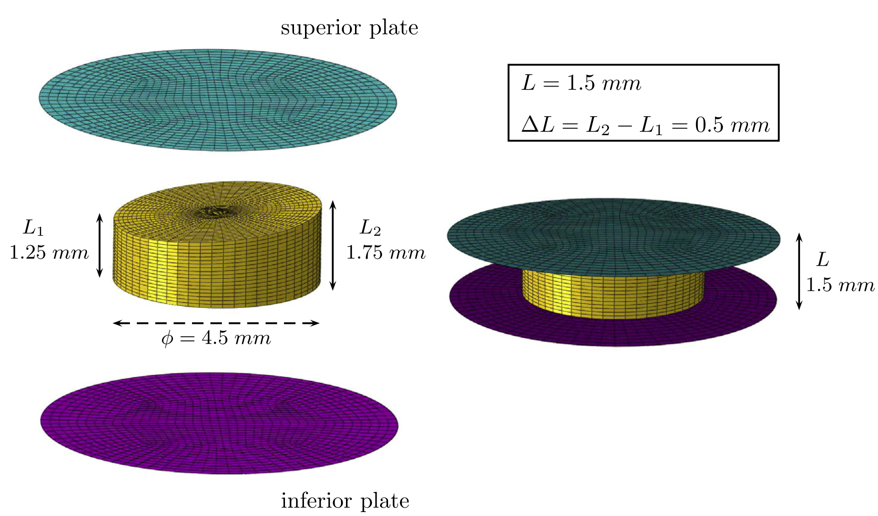

Fig. 2. Finite element model used to simulate a specimen with ϕ=4.5 mm, and L=1.5 mm and a variation in thickness of 0.5 mm (case E2). At the left, each component of the model is shown separately (specimen with its dimensions, superior and inferior plates). At the right, the starting point of the test (after solving the contact interference problem) is shown.