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Short communication

Fitted hyperelastic parameters for Human brain tissue from reported tension, compression, and shear tests

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ABSTRACT

The mechanical properties of human brain tissue are the subject of interest because of their use in understanding brain trauma and in developing therapeutic treatments and procedures. To represent the behavior of the tissue, we have developed hyperelastic mechanical models whose parameters are fitted in accordance with experimental test results. However, most studies available in the literature have fitted parameters with data of a single type of loading, such as tension, compression, or shear. Recently, Jin et al. (*Journal of Biomechanics* 46:2795 – 2801, 2013) reported data from ex vivo tests of human brain tissue under tension, compression, and shear loading using four strain rates and four different brain regions. However, they do not report parameters of energy functions that can be readily used in finite element simulations. To represent the tissue behavior for the quasi-static loading conditions, we aimed to determine the best fit of the hyperelastic parameters of the hyperfoam, Ogden, and polynomial strain energy functions available in ABAQUS for the low strain rate data, while simultaneously considering all three loading modes. We used an optimization process conducted in MATLAB, calling iteratively three finite element models developed in ABAQUS that represent the three loadings. Results showed a relatively good fit to experimental data in all loading modes using two terms in the energy functions. Values for the shear modulus obtained in this analysis (897 – 1653 Pa) are in the range of those presented in other studies. These energy-function parameters can be used in brain tissue simulations using finite element models.

1. Introduction

The mechanical behavior of human brain tissue is the subject of intense scientific research because the results of these studies may be used, for instance, to analyze trauma or to produce recommendations for improved treatment of diseases. In experimental studies, brain tissue has shown a nonlinear, viscoelastic, and anisotropic, mechanical behavior (Feng et al., 2013; Miller and Chinzei, 1997; Prevost et al., 2011). In addition, it is a highly compliant material, which makes its mechanical characterization a challenging task.

There have been several experimental studies of human brain tissue (Chatelin et al., 2012; Donnelly and Medige, 1997; Fallenstein et al., 1969; Franceschini et al., 2006; Kruse et al., 2008; Nicolle et al., 2004; Prange and Margulies, 2002; Prange et al., 2000; Sack et al., 2008, 2009; Schiavone et al., 2009). However, with the exception of a few of these aforementioned studies (Franceschini et al., 2006; Prange and Margulies, 2002; Prange et al., 2000), each reported single-mode experiments, with tests in just tension, compression, or shear. It has been shown that the elastic parameters of hyperelastic energy functions that produce a good fit of independent single test data, such as uniaxial tension or compression, may yield different predictions under biaxial or three-axial loading (Smith and García, 2013). Hence, it appears to be essential to obtain strain energy function parameters that can simultaneously fit results of independent experiments.

Recently, Jin et al. (2013) reported results of tests on human brain tissue under uniaxial tension, pure shear, and uniaxial compression in the cerebral cortex, thalamus, corpus callosum, and corona radiata. Unfortunately, this valuable set of experimental data was not fitted with theoretical constitutive equations that can be readily used in finite element simulations. Hence, the objective of this study was to obtain parameters of hyperelastic strain energy functions by fitting the experimental data reported by Jin et al. (2013).

2. Materials and methods

Briefly, Jin et al. (2013) tested 240 human brain tissue specimens under uniaxial tension ($n=72$), uniaxial compression ($n=72$), and pure shear ($n=96$) up to 50% nominal strain. Cuboidal samples with a squared section of 14 mm per side and 5 mm thickness were extracted from 9 postmortem human subjects from the

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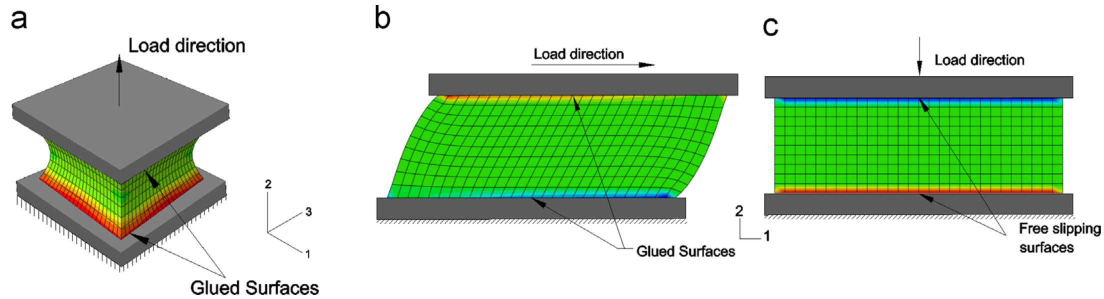

Fig. 1. Finite element models and boundary conditions adopted for the fitting process of the experimental data reported by Jin et al. (2013) for (a) tension, (b) shear, and (c) compression.

cerebral cortex, thalamus, corpus callosum, and corona radiata, where the first two locations were gray matter and the other two are white matter. The specimens were tested under three strain rates—low (0.5 s^{-1}), medium (5 s^{-1}), and high (30 s^{-1}) — with load applied on the 14 mm × 14 mm faces (Fig. 1). For the white matter, tests were conducted along three perpendicular directions defined with respect to fiber orientation. The results of their study showed no significant differences among properties for the cerebral cortex, thalamus, and corpus callosum. However, the corona radiata was found to be stiffer in tension and compression. The only directional dependence was found in white matter under shear loading.

Following the experimental setup of Jin et al. (2013), three groups were considered in our analyses. The first corresponded to the gray matter characterized by the results for the cerebral cortex and thalamus. The second corresponded to the white matter, including results for the corpus callosum and corona radiata. A third group was analyzed with the results for the corona radiata only, as this tissue is significantly stiffer that the others. To exclude viscoelastic effects, we considered only the slowest strain rate data in our analyses.

Given the size of the samples and the restrictions caused in the fixtures used by Jin et al. (2013), the experimental stress fields did not exactly correspond to uniaxial stress or pure shear. In fact, the top and bottom faces of the specimens under tension and shear were glued to the static and movable parts of the testing machine, whereas in compression no glue was used to allow free expansion of the specimens (Jin et al., 2013). Hence, to perform the fitting process, we developed finite element models using the commercial program ABAQUS (Simulia Corp., Providence, RI, USA). The dimensions, shapes, and boundary conditions of the models were consistent with those reported by Jin et al. (2013).

For the tension test, following a mesh convergence study, a three-dimensional model composed of 3872 linear brick (C3D8R) elements was used (Fig. 1a). For the shear and compression tests, following a mesh convergence study, two plane strain models composed of 280 quadrilaterals (CPS4R) elements were used (Figs. 1b,1c). These plane models were defined after a comparison of the reaction forces with those obtained with corresponding three-dimensional models showing differences less than 1%. To account for the friction that occurred between the plates and the tissue in the compression test, we examined two plane models: one with a free slipping condition and a second that included a friction coefficient of 0.09, as reported by Rashid et al. (2012a). From this comparison, it was determined that the mean difference in the reaction force from the two models was less than 3.6%, so a free slipping model was preferred due to the shorter processing time compared to the model with friction.

Three hyperelastic energy functions were chosen that are available in ABAQUS and have previously been used to fit single-mode experimental results of brain tissue. The first strain energy potential considered was the hyperfoam function, defined as

$$U=\sum_{i=1}^{N}\left[\frac{2\mu_i}{\alpha_i^2}(\lambda_1^{\alpha_i}+\lambda_2^{\alpha_i}+\lambda_3^{\alpha_i}-3)+\frac{1}{\beta_i}(J^{-\alpha_i\beta_i}-1)\right] \tag{1}$$

where λ_i are the principal stretches; J is the determinant of the deformation gradient tensor; N is the number of terms; and μ_i, α_i, and β_i are material parameters. The second was the Ogden strain energy potential, defined as

$$U=\sum_{i=1}^{N}\frac{2\mu_i}{\alpha_i^2}(\overline{\lambda}_1^{\alpha_i}+\overline{\lambda}_2^{\alpha_i}+\overline{\lambda}_3^{\alpha_i}-3)+\sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i} \tag{2}$$

where $\overline{\lambda}_i$ are the deviatoric principal stretches and D_i are material parameters. In these two strain energy functions, the parameters μ_i are related to the initial shear modulus, the parameters α_i modify the degree of nonlinearity of the stress-strain curves, and the parameters D_i and β_i may be used to adjust the compressibility of the material.

A unique Poisson's ratio is associated with the parameter D_1 of the Ogden energy function; for the hyperfoam function a different Poisson's ratio is calculated for each value of β_i. To determine a unique, effective value for the Poisson's ratio ν_{ef} of the hyperfoam function, we conducted a finite element analysis of a model under uniaxial loading and infinitesimal strains for each set of the fitted properties.

The third strain energy potential considered was the polynomial strain energy potential, defined as

$$U=\sum_{i+j=1}^{N}C_{ij}(\bar{I}_1-3)^i(\bar{I}_2-3)^j+\sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i} \tag{3}$$

where C_{ij} are material parameters, and $\bar{I}_1$ and $\bar{I}_2$ are the first and second deviatoric strain invariants, defined as

$$\bar{I}_1=\overline{\lambda}_1^2+\overline{\lambda}_2^2+\overline{\lambda}_3^2 \tag{4}$$

$$\bar{I}_2=\overline{\lambda}_1^{-2}+\overline{\lambda}_2^{-2}+\overline{\lambda}_3^{-2}. \tag{5}$$

The initial shear modulus μ_0 and bulk modulus K_0 are given in terms of the function parameters as

$$\mu_0=2(C_{10}+C_{01}) \tag{6}$$

$$K_0=\frac{2}{D_1} \tag{7}$$

respectively. Note that the deviatoric stretch ratios, defined as

$$\overline{\lambda}_i=J^{-1/3}\lambda_i \tag{8}$$

appear in the latter two strain energy functions, as the hyperelastic formulation of the ABAQUS separates the energy function into the deviatoric and hydrostatic components.

To find the parameters of the functions that simultaneously fit the three independent experiments, we defined a target function F_t as the sum of the absolute deviations between the experimental and model reaction forces at each strain level (corresponding to 10 strain levels, from 0.05 to 0.5 mm/mm in increments of 0.05) for tension (t), compression (c) and shear (s). Because of the differences of the reaction forces magnitude in the different tests, every term of the target function was normalized by dividing by the mean value of the response.

$$F_t=\frac{\sum_{i=1}^{10}|Ft_i^{model}-Ft_i^{test}|}{\frac{1}{10}\sum_{i=1}^{10}|Ft_i^{test}|}+\frac{\sum_{i=1}^{10}|Fc_i^{model}-Fc_i^{test}|}{\frac{1}{10}\sum_{i=1}^{10}|Fc_i^{test}|}+\frac{\sum_{i=1}^{10}|Fs_i^{model}-Fs_i^{test}|}{\frac{1}{10}\sum_{i=1}^{10}|Fs_i^{test}|}. \tag{9}$$

The minimization was achieved using the optimization function fminsearch of MATLAB (Mathworks Inc, Natick, MA, USA) that was implemented to iteratively run the three finite element models in ABAQUS.

3. Results

An initial pilot study using one term for each of the three strain energy functions showed a poor fitting of the tension tests. Hence, two terms ($N=2$) were chosen for each the three hyperelastic strain energy functions.

The hyperfoam, Ogden, and polynomial functions, each with two terms, yielded a relatively good fit of the experimental tension (Fig. 2), compression (Fig. 3), and shear data (Fig. 4). The best fit was attained with the hyperfoam function ($R^2>0.97$), followed by the Ogden function ($R^2>0.92$), and then the polynomial function ($R^2>0.80$) (Table 1). In particular, the hyperfoam function provided a better agreement of the change in curvature shown in the experimental tension curves (Fig. 2a).

The Poisson's ratios were similar for each of the three strain energy function, with values of ~0.38 for the hyperfoam function, ~0.42 for the Ogden function, and ~0.44 for the polynomial functions (Table 1). The shear moduli from the polynomial function were 14 – 39% higher than those from the hyperfoam function,