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Development of a Visco-hyperelastic Constitutive Law for Brain Tissue based on Finite Element Simulation and Optimization Methodology

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Abstract: The objective of this study was to develop a viscous-hyperelastic constitutive law for the FE modeling of brain tissue.Material properties of a visco-hyperelastic constitutive model were determined via the application of FE simulations and optimization methodology. Basic FE models were developed according to referred dynamic uniaxial tension tests of brain tissue with uniform strain rates of $30s^{-1}$ and $90s^{-1}$ up to 30% strain. The optimization objective was to minimize fitting errors between strain-stress curves predicted by FE simulations and corresponding curves measured from referred experiments. Material constants of a visco-hyperelastic constitutive model was defined as constant or design parameters for the optimization procedure, with given values or design domain. Uniform Latin Hypercube algorithm was applied to generate the initial group of FE models, and an improved multi-objective genetic algorithm (MOGA-II) was applied as the optimization strategy.Results indicates that the strain-stress curves predicted by the optimized FE models were located in experimental corridors when the strain higher than 15% for both strain rates of $30s^{-1}$ and $90s^{-1}$. Thus, the proposed visco-hyperelastic constitutive law could be applied in FEHMs for the prediction of intracranial mechanical responses at injury levels.

Keywords: finite element modeling, viscous effect, hyperelasticity, material constitutive model

1 Introduction

Road traffic accidents (RTAs) are serious public health problems of modern societies all over the world. According to the latest the World Health Organization report [1], there are approximately five million people suffered from traffic injuries every year; among which, approximately one million people are dead. Traumatic brain injuries (TBIs) are common types of traffic injuries, and serious TBIs often result in deaths. For example, there were approximately 1.7 million people sustained TBIs annually on average between 1997 and 2007 in the United States, while an average of about 52,000 civilizations deed from TBI-related injuries each year [2].

In pasted ten years, finite element head models (FEHMs) have been widely used for studies exploring intracranial dynamics related to TBIs. For instance, FEHMs have been used for the investigation of TBs resulting from head collisions in real world accidents, from which brain injury criteria and thresholds have been suggested [3,4]. For the prediction of intracranial response as well as the quantitative injury criteria, the mechanical behavior of biological tissues, especially the brain tissue, should be mimicked precisely. In recent years, visco-hyperelastic constitutive models have been used to describe the nonlinear mechanical behavior of the brain tissue in FEHMs [4-6]. However, the material properties of the visco-hyperelastic constitutive model were identified by separated to a basic hyperelastic model and a linear viscoelastic model in previous studies. And the performance of that strategy as well as those proposed visco-hyperelastic constitutive laws were not fully validated.

Therefore, a method based on finite element (FE) simulations and the optimization methodology were applied for the development of a visco-hyperelastic constitutive law of brain tissue. The objective of the optimization procedure was to mimic experimental strain-stress relationships at different strain rates via the application of the pre-developed constitutive law.

2 Materials and methods

A method based on the finite element model (FEM) and an improved multi-object genetic algorithm (MOGA-II) [7] was applied for the development of a visco-hyperelastic constitutive law. The optimization procedure of the FEM-MOGA method which was used to determine material variables of the visco-hyperelastic constitutive model was illustrated in Figure

1. Firstly, a basic viscous-hyperelastic material model and referred material mechanical tests were selected. A “design domain” of material properties was defined base on published experimental data. The Uniform Latin Hypercube was applicated for the generation of initial sets of material properties. And the MOGA-II was applied as the optimization strategy in this study.

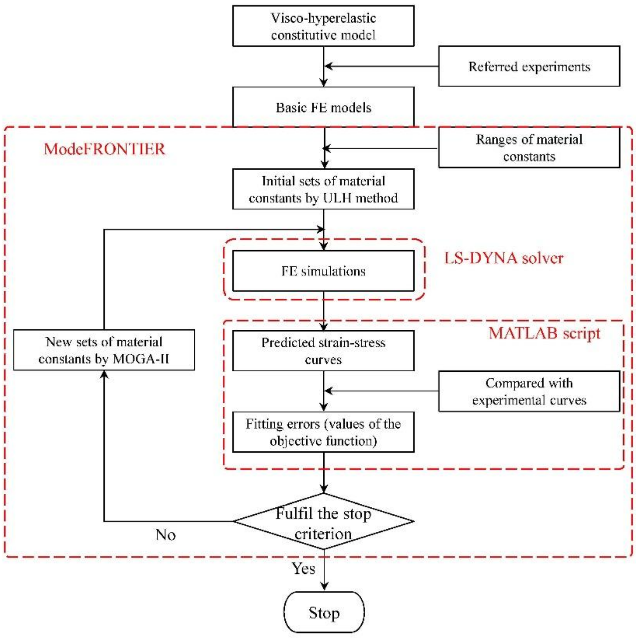

Figure 1. Procedure of the FEM-MOGA method for identification of material parameters. The dashed line boxes indicate used commercial programs for corresponding procedures.

2.1 Visco-hyperelastic constitutive model

Visco-hyperelastic constitutive models have been used to describe the nonlinear mechanical behavior of biological tissues. Generally, visco-hyperelastic constitutive models were developed based on a basic hyperelastic model with the consideration of the viscous effect. Classically, a strain energy density W is defined as a function of the material deformation for the hyperelastic model. In this study, the Ogden model was introduced as the basic hyperelastic model. The strain energy density of the one-term Oden material model is defined as a function of the relative volume, J and bulk modulus, K [8]:

$$W = \frac{\mu}{\alpha}(\lambda_1^\alpha + \lambda_2^\alpha + \lambda_3^\alpha - 3) + K(J - 1 - \ln J) \tag{1}$$

where λ_i (i=1, 2, 3) are the principal stretch ratios, μ and α are material constants of the Ogden model. The stress tensor in terms of the second Piola-Kichhoff stress is given by:

$$\sigma_{ij} = \frac{1}{2}\left(\frac{\partial W}{\partial E_{ij}} + \frac{\partial W}{\partial E_{ji}}\right) \tag{2}$$

where Eij indicates the Green’s strain tensor.

The viscous effects, inducing the rate effect, stress relaxation and strain creep are critical characteristics of biological materials, and play a significant role on the mechanical behaviors. Viscous effect has been taken into account by previous researches through linear viscoelasticity by a convolution integral as proposed by Fung (1981) [9] for the developing of the quasi-linear visco-elastic (QLV) material model:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^e(\varepsilon) + \boldsymbol{\sigma}^v(\varepsilon, t) \tag{4}$$

$$\sigma_{ij}^v = \int_0^t G_{ijkl}(t-\tau)\frac{\partial E_{ij}}{\partial \tau}d\tau \tag{5}$$

$\boldsymbol{\sigma}^e$ is the stress tensor determined by the Ogden hyperelsticmdoel, and $\boldsymbol{\sigma}^v$ is the stress tensor induced by viscous effects. $G_{ijkl}(t)$ are material relaxation functions. In this study, the stress relaxation function of the linear viscoelastic model is presented by the Prony series:

$$\mathrm{G(t)} = \sum_{i=1}^N G_i e^{-\beta_i t} \tag{6}$$

where G_i are shear modulus,$\beta_i$are decay constants.

2.2Referred mechanical tests of brain tissue

Recently, dynamic uniaxial extension tests of brain tissue were conducted by Rashid et al. [10] using a self-developed high rate tension device (RHRD). Briefly, cylindrical specimens, containing mixed white and gray matter, were cut from fresh porcine brains with the average diameter and height of 15.1 mm and 10 mm. Then, the prepared specimen was placed between the upper and lower plates of the HRTD dynamic extension tests were performed at uniform velocities while the measured strain rates varied from 30s^{-1} to 90s^{-1}. In this study, those experiments with a low strain rate of 30 s^{-1} and a high strain rate of 90 s^{-1} were selected as the referred experiments for the identification of material parameters of the visc-ous-hyperelastic material model.

2.3 FE modeling

According to referred experiments, FE models were developed in the environment of LS-DYNA (LSTC, USA). Hexahedral elements were applied for the modeling of the specimen as well as the plates. The boundary and loading conditions were defined precisely following the experiments' setup. The upper and lower surface of the specimen were fixed with corresponding plates by share nodes. During the test, the up plate was fixed, while a described motion in the vertical direction the was assigned to the lower plate. The section force between the specimen and the upper plate was record for a calculation of the engineering strain-stress curve. Two basic FE models were development by applying extension strain rates of 30s^{-1} and 90 s^{-1}, respectively.

A mesh conversional analysis (MCA) of developed FE models was also conducted. Four FE models with average element edge sizes of 2 mm, 1 mm, 0,5 mm and 0.25 mm were simulated, while uniaxial extension were imposed following the referred experiments. Enringing stress at a strain of 30% were calculated for the MCA.

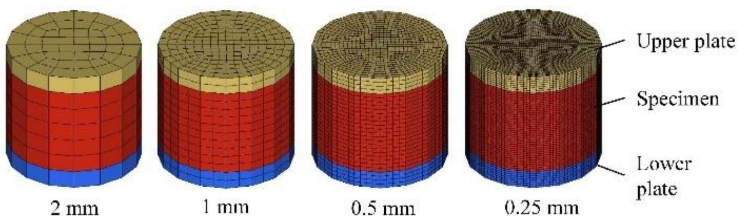

Figure 2 FE models for the MCA

2.4Optimization problems

An objective function ***F***, which aimed to minimize the errors between strain-stress curves expected by FE and experimental average curves, was defined. As shown in Eq.8-9, the least square method was employed for the calculation of fitting errors:

$$\boldsymbol{F} = [F_l, F_h] \tag{7}$$

$$F_l = \sum_{i=1}^{N}(f_{l\_s\_i} - f_{l\_e\_i})^2 \tag{8}$$

$$\mathrm{F}_h = \sum_{i=1}^{N}(f_{h\_s\_i} - f_{h\_e\_i})^2 \tag{9}$$

where F_l and F_h the indicate fitting error associated with the lower and higher strain rate test, respectively. And, $f_{l\_s\_i}$ are values of strain-stress curves predicted by FE simulations, $f_{h\_s\_i}$ are corresponding values measured from referred experiments. In this study, 30 points were selected evenly from each curve for the calculation of fitting errors.

Table 1 Design domain of material variables for the visco-hyperelastic constitutive model

Material Constants	Status	Lower Bound	Upper Bound
μ (kPa)	Constant	0.05	
α	Design Parameter	5	30
G_1 (kPa)	Design Parameter	10^{-3}	200
G_2	Design Parameter	10^{-3}	200
β_1 (s^{-1})	Constant	10^{-9}	
β_2 (s^{-1})	Design Parameter	10^{-7}	0.09

Firstly，a value of 0.05 kPa which stands an approximately value measured from quasi-statistic mechanical tests was assigned to the material constants, μ [11]. Meanwhile, a two-term Pony series was employed to describe the relaxation function, and a value of $10^{-9}s^{-1}$ was assigned to β_1; thus, the G_1 represents the long-term shear modulus of the linear viscoelastic model. Other material variables, α of the Ogden hyperelastic model and the G_1, G_2, β_2 were design parameters need to be determined. The range of values of all material variables are listed in Table1.

The Uniform Latin Hypercube (ULH) sampling algorithm was used for the generation of initial 24 sets of material variables. An improved multi-objective genetic algorithm (MOGA-II) wasemployedfor the optimization procedure. The MOGA-II was a more effective MOGA that uses a smart multi-search elitism, and could be able to preserve some excellent solutions without bringing to prematureconvergence into local optimal fronts. And 30 generations were assigned for the MOGA-II.

3 Results

A set of material variables with moderate stiffness level was applied for the MCA. As illustrated in Figure 3, a clear conversational trend of the predicted engineering stress could be observed with the average element edge size reduced from 2 mm to 0.25 mm, as well as the predicted stress contours (Figure 4). However, with the reduction of the average element edge size the computer time consuming was increased approximately exceptionally by using the same PC with a CPU of i7-6820HQ. Considering that large computation required from the MOGA-II, the average element edge size of 1 mm was selected for FE models in this study.

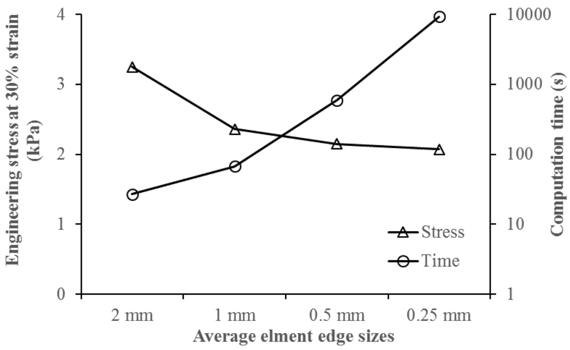

Figure 3 Results of the MCA

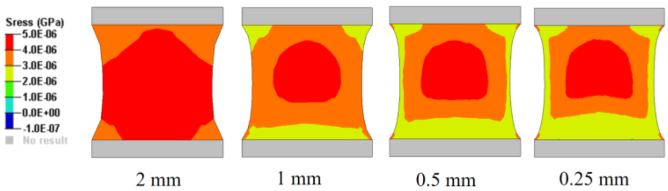

Figure 4Contours of predicted stress in the extension direction at the middle cross section of the specimen

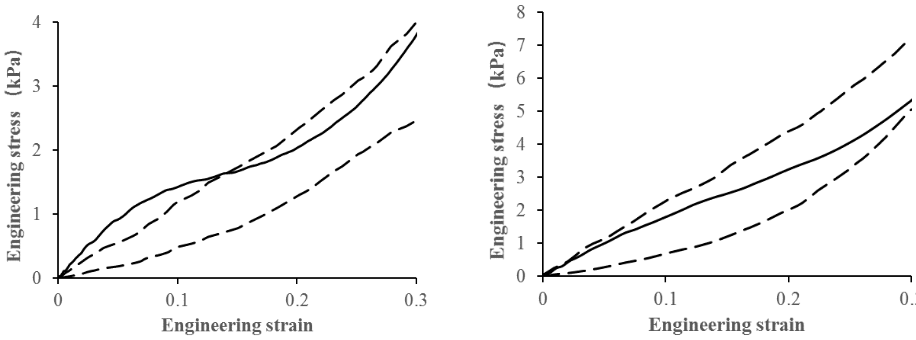

Figure 5 Comparison of the strain-stress relationships predicted by FE simulations and corridors measured from referred experiments. Solid lines indicate the FE predicted strain-stress curves, and dashed lines indicate the experimental corridors.

Totally, 720 FE simulations were calculated for each strain rate for the 30 generations optimization procedure. Sets of Pareto optimal parameters were suggested as the Pareto front by the MOGA-II. A set of material variables was selected from the Pareto front considering both of less fitting error at the lower and high strain rate, as well as the computational stability (Table 2). The strain-stress predicted by the FE model with the optimal material properties are illustrated in Figure 5. As shown in Figure 5(a), the predicted strain-stress curve is located in the experimental corridor when the extension strain large than 15% with a strain rate of 30 s^{-1}. For the strain rate of 90 s^{-1}, the predicted strain-stress curve is located in the experimental corridor perfectly (Figure 5(b)).

Table 2 optimal material constants of the visco-hyperelastic constitutive law

Material Constants	Values
μ (kPa)	0.05
α	13.64
G_1 (kPa)	0.031
G_2	10.07
β_1 (s^{-1})	10^{-9}
β_2 (s^{-1})	729

4 Discussions

In this study, the FEM-MOGA method was employed for the determination of the material variables of a viscous-hyperelastic constitutive model. And objective of the optimization was to fitting the strain-stress curves measure from dynamic uniaxial extension up to 30% strain with a lower strain rate of 30 s^{-1} and a higher strain rate of 90s^{-1} by using the FE model assigned with developed visco-hyperelastic constative law. In precious studies, the material properties of the visco-hyperelastic constitutive model were identified with the model separated to a basic hyperelastic model and a linear viscoelastic model [3,6,12]. Stead of those previous strategies, the basic hyperelastic model and the linear viscoelastic model were regard as an integral material model.

As illustrated in Figure5, the strain-stress curves predicted by the optimal FE simulation could mimic mechanical behavior of the brain tissue in the dynamic uniaxial extension tests with a strain rate of 30 s^{-1} or 90 s^{-1} and strain between 15% and 30%. In addition, moderate or serious TBIs often occurred associated with the intracranial strain larger than 10% or 15% [3, 13]. Thus, the current proposed visco-hyperelastic constitutive law is acceptable for the investigation of moderate or serious TBIs.

For future studies, other types of experiments associated with material mechanical characteristic should be taken into account for the improvement of the constitutive law.

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