Research on Uniaxial Tension Test of Brain Tissue

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Abstract. Corresponding to low targeting accuracy due to tissue deformation during the process of electrode insertion in sub-thalamic nucleus deep brain stimulation (DBS), biomechanical properties of brain tissue are essential to investigate. In this paper the isolated porcine brain tissue is used in the uniaxial tensile test. Moreover, cylindrical samples of diameter (10 mm) and height (10 mm) are used to measure tensile length by single degree of axis at 5mm/s, until specimen was broken. The stretch ratio of brain tissue has been explored. The material failure criterion parameters, $K$, $\Gamma_1$, $\Gamma_2$, of MAT-QUASILINEAR-VISCOELASTIC biological material model in LS-DYNA are fitting calculated according to the experimental results. Six uniaxial failure data obtained from uniaxial tests are 4.81, 5.00, 4.07, 4.62, 4.28, 4.45 respectively. Three failure material constants $\Gamma_1$, $\Gamma_2$, $K$ are -0.0084, -3.1944, -4.8095. The failure criterion is being implemented in LS-DYNA to simulate brain tissue.

Introduction

DBS is effective for neurological conditions and changes the abnormal discharge of neurons by using implanted electrodes to stimulate special nerve nuclei. In the process of implantation, there are two main reasons cause low accuracy of puncture, the deformation of tissue and deflection of electrode sleeve. It’s a major concern how to make model’s changes approximate to true deformation in modeling and simulation. So, it is particular important to research on the mechanical properties of brain tissue.

The brain is a kind of heterogeneous and anisotropic soft tissue with elastic, viscoelastic, linear, nonlinear biomaterial properties [1]. The accurate characterization of material properties have a pivotal role in the analysis of pathology, the formulation of strategies and planning of rehabilitation in neurosurgery. In tensile aspect, Rashid conducted an uniaxial tension experiment on porcine brain at strain rates of 30, 60 and 90/s up to 30% strain. They found the brain tissue showed stiffer response with increasing strain rates and used one-term Ogden model to simulate the hyperelastic and viscoelastic behavior of brain [2]. Miller developed a mathematical analysis deformation model which shows isotropic, incompressible and small displacement property through using experiments on porcine brain samples [3,4]. MAT_QUASILINEAR_VISCOELASTIC from LS_DYNA is a quasi-linear, isotropic, viscoelastic material based on one-dimensional model by Feng [5]. A sample which from pig brain is used during tension tests at quasistatic velocity (5mm/s) in this paper. The ratio (stretch ratio) between ultimate length at fracture and initial length is investigated. Moreover, the constant parameters of the failure model are calculated by MATLAB.

Theory Analysis

A material particle initially at $M_0(x_0, y_0, z_0)$, as shown in Fig.1, $M_i(x(t), y(t), z(t))$ is the coordinates of the particles after deformation in same Cartesian coordinate system.
Choosing $\nabla$ represents the deformation gradient of material, $\nabla$ is

$$\nabla = \begin{pmatrix} g_{3105} & g_{3014} & \cdots \\ g_{3284} & \cdots & \cdots \\ \vdots & \cdots & \cdots \end{pmatrix}.$$  

(1)

Making $C$ represents right Cauchy-Green strain tensor, $C$ is

$$C = \nabla^T \nabla.$$  

(2)

There are three invariants of the right Cauchy-Green strain tensor about isotropic elastic object. The invariants are:

$$I_1 = C_{\alpha\alpha}.$$  

(3)

$$I_2 = \frac{1}{2} \left( (C_{\alpha\alpha})^2 - C_{\alpha\beta}C_{\beta\alpha} \right).$$  

(4)

$$I_3 = \det(C).$$  

(5)

The material failure criterion in LS-DYNA model is based on the conservation of energy. The material will fail, if the tensile energy reaches maximum value. So, a failure equation with respect to strain invariants can be established.

$$F(I_1, I_2, I_3) = 0.$$  

(6)

For incompressible materials, $I_3 = 1$, the simplification of Eq. 6 is

$$F(I_1, I_2) = 0.$$  

(7)

The failure criterion for hyperelastic solids according to Feng’s [6] theory is

$$(I_1 - 3) + \Gamma_1 (I_1 - 3)^2 + \Gamma_2 (I_2 - 3) - K = 0.$$  

(8)

Strain invariants can also be expressed by three principal stretch ratios ($\lambda_1$, $\lambda_2$, $\lambda_3$).

$$I_1 = \lambda_1^4 + \lambda_2^4 + \lambda_3^4.$$  

(9)

$$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_1^2 \lambda_3^2 + \lambda_2^2 \lambda_3^2.$$  

(10)

The load can only be applied in one direction during uniaxial tension or compression experiments, so, it is assumed that the stretch ratios in the other two directions are equal, $\lambda_2 = \lambda_3$. Brain tissue can also be considered an incompressible material [7,8].
\[ \lambda_1 \lambda_2 \lambda_3 = 1. \]  
Eq. 8 is converted to then

\[
\left( \frac{(\lambda^3+2)}{\lambda} - 3 \right) + \Gamma_1 \left( \frac{\lambda^3+2}{\lambda} - 3 \right)^2 + \Gamma_2 \left( \frac{2\lambda^2+1}{\lambda} - 3 \right) - K = 0. 
\]  

**Extension Experiment Set-up**

**Specimen Preparation**

The porcine brains should meet the following conditions: 1) Derived from approximately six months old pigs and were collected about six hours after death. 2) Soaking in the cerebrospinal fluid and maintain the low temperature environment of 4~5°C during transportation. 3) Restore brain tissue approximately 30 minutes at a room temperature before taking experiments. 4) Tested within four hours.

In this paper, the diameter and height of specimens were 10mm and 10mm [9], respectively.

**Experimental Procedure**

The glue (Cyanoacrylate glue, 502, De Li) was used to attach the brain specimen with the platens before tests. Adjust the position of test devices to make sure the sample upright. The NANO17 force sensor (Resolving power: 3mN, NANO17-SI-12-0.12, ATI Industrial Automation) was connected with upper platform. The output signal of the force is set to zero through the computer terminal, and the sampling frequency is 100Hz. Top platen was lowered slowly apply a preload force about 10mN to the sample so as to touch the top of surface of the specimen. After one minute, the specimen was stretched by moving unit (stroke length: 100 mm, maximum velocity: 10 mm/s, repositioning precision: 1 um, M-L01.4A0, Physik Instrument) at the speed of 5mm/s, until brain tissue is broken. Repeated test six times, the fractural length and initial length were recorded respectively.

**Results**

Six tensile tests on brain specimens were performed at the velocity of 5 mm/s to obtain uniaxial stretch ratios. The test numbers are #1, #2, #3, #4, #5, #6. Force (N) and displacement (mm) data measured directly at a sampling frequency of 100 Hz were counted in the same Cartesian coordinate system. The graph is shown in Fig. 2. When top platform moving up, the force increased with stretching height until approximately ~10mm height. The stress of brain tissue reached the maximum value and tensile energy run up to limit value. Necking phenomenon began to occur in the middle of sample. Meanwhile, the tensile force shown a decreasing trend with increasing height until fractured, which reached an approximately constant value, eventually. The steady value was bigger than zero, caused by a partial specimen remaining on the upper platform.
Here, \( L \) is the ultimate length of tissue when broken.

\[
L = L_0 + \Delta L.
\]  
(13)

Where \( L_0 \) is initial length and \( \Delta L \) is displacement in the fracture process. Moreover, the stretch ratio \( (\lambda) \) can be obtained and is shown in Table 1.

\[
\lambda = \frac{L}{L_0}.
\]  
(14)
Table 1. Initial length, broken length, stretch ratio of samples.

<table>
<thead>
<tr>
<th>Number</th>
<th>Initial Length (mm)</th>
<th>Broken Length (mm)</th>
<th>Stretch Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>10±1</td>
<td>47.4±3</td>
<td>4.81±0.78</td>
</tr>
<tr>
<td>#2</td>
<td>10±1</td>
<td>49.2±3</td>
<td>5.00±0.81</td>
</tr>
<tr>
<td>#3</td>
<td>10±1</td>
<td>40.1±3</td>
<td>4.07±0.71</td>
</tr>
<tr>
<td>#4</td>
<td>10±1</td>
<td>45.5±3</td>
<td>4.62±0.76</td>
</tr>
<tr>
<td>#5</td>
<td>10±1</td>
<td>42.1±3</td>
<td>4.28±0.73</td>
</tr>
<tr>
<td>#6</td>
<td>10±1</td>
<td>43.7±3</td>
<td>4.45±0.74</td>
</tr>
</tbody>
</table>

The parameters of failure criterion were estimated with application of least-square method, three constants ($\Gamma_1$, $\Gamma_2$, $K$) were -0.0084, -3.1944, -4.8095.

Conclusions

Through the six groups of tensile experiments, it has been demonstrated that force-displacement curve can be used to calculate the stretch ratio of porcine brain. The unidirectional material failure model of tissue was completed according to experimental data. It provides a material model for LS-DYNA to simulate and analysis puncture procedure in the future. Fitting failure criterion of soft tissue just in one direction is sufficient to adequate to accurately model brain's characteristic. Further work will focus on biaxial tension or compression test to acquire more suitable model for simulating.

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References


