The Instantaneous Elastic Response in Compression and Tension in Porcine Brain

Feng ZHAO, Qing-wei CHEN, Jun ZHOU, Chun-yang PAN

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. Knowing the properties of brain can be used in finite element simulations to predict the deformation of tissue under different operating conditions. It provides a forecasting mechanism for target localization. Firstly, cylindrical samples of diameter (10 mm) and height (10 mm) are adopted uniaxial compression test at 5 mm/s up to 35% strain. Go back to the starting place and keep 5 s. Secondly, uniaxial tensile tests were carried out under the same experimental conditions up to 25% strain. The main content of this research is defining the instantaneous elastic response in compression and tension. The polynomial function of MATLAB is used to calculate the engineering stress-strain curve according to experimental data. The linear polynomial can’t satisfy the accurate expression of results. The instantaneous elastic response’s parameters obtained in the study will perfect modelling of MAT_QUASILINEAR_VISCOELASTIC in LS-DYNA.

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 reason 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, the mechanical properties of brain tissue should receive greater attention.

Most scholars have done extensive research on the mechanical properties of brain tissue by compression, tension, shear, indentation-relaxation and other test methods. However, a study on the combine compression and tension of same sample is less than single way. In compression aspect, Laksari have adopted Quasi-linear viscoelastic model of bovine brain tissue under step-and-hold uniaxial compression with 10 s⁻¹ strain rate and 20 s hold time to investigate the constitutive model of brain at high velocity.¹ Tamura have conducted an uniaxial and unconstrained compression experiment at strain rates of

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1, 10, 50/s, they concluded that the character of brain become harden as the impact velocity increase. The conclusion less directional properties of brain tissue with larger sample can be used to infer damage in other directions by one-way condition. In tension 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. Miller developed a mathematical analysis deformation model which shows isotropic, incompressible and small displacement property through using experiments on porcine brain samples. In LS-DYNA, symmetry is not assumed if only the tension side is defined. Therefore, the response in tension or compression only may lead to nonphysical behavior in other aspect.

In this paper, samples that diameter and height are 10 mm which from adult porcine brain is used during compression and tension test at 5 mm/s. In the same coordinate, draw the relation of engineering stress and strain curve. Using nonlinear polynomial function that contains only odd terms to fit the stress-strain curve. The generated parameters of MAT_QUASILINEAR_VISCOELASTIC material model was calculated by MATLAB with 95% confidence intervals.

EXPERIMENT SET-UP

Specimen Preparation

All procedures of treating were approved by Shandong University Animal Care and Use Committee. To accurately measure the biomechanical of pig brain, the sample should meet the following conditions:

- Derived from approximately six months old pigs and were collected about six hours after death.
- Soak in the cerebrospinal fluid and maintain the low temperature environment of 4~5°C during transportation.
- Restore brain tissue approximately 30 minutes at a room temperature before taking experiments.
- Tested within four hours.

The whole globular porcine brain has been separated using a surgical scalpel along symmetry axis. Figure 1.a is the right-hemisphere. In order to easy make specimens and avoid the effects of superficial sulci and gyri of brain, the right-hemisphere would have been cut follow the puncture trajectory of Deep Brain Stimulation. Figure 1.b shows the cylindrical samples of diameter and height are 10mm in experiments. Steel pipe designed by ourselves with sharp edges and smooth groove have been adopted to improve the precision of samples, as shown in Figure 1.c.

![Figure 1. a. The right-hemisphere was cut by surgical scalpel from symmetry axis and the sampling location. b. The cylindrical samples of diameter and height are 10mm. c. Customized cutter.](image)
### Experimental Procedure

Figure 2 shows the schematic diagram of the platform. There are four parts: XY mobile worktable, Z-axis moving unit (stroke length: 100 mm, maximum velocity: 10 mm/s, repositioning precision: 1 um, M-L01.4A0, Physik Instrument, Germany), control unit, A six degree of freedom force sensor (Resolving power: 3mN, NANO17-SI-12-0.12, ATI Industrial Automation, USA). A rigid plastic indenter was fixed to the sensor by a customized holder.

The glue (Cyanoacrylate glue, 502, De Li) was used to contain the brain specimen and upper-under platform. Adjusting the XY mobile worktable to avoid producing the torque of others degree. Firstly, setting the sampling frequency of the sensor to 100Hz and the sensor was reset to zero. Next, the rigid plastic indenter was continually moved down at the velocity of 5mm/s up to 35% engineering strain. Total force and displacement data were collected by sensor. Let the indenter return to the initial point at same speed. To reduce the effect of viscoelastic of soft tissue on the results (according to previous compression test, the shear modulus can achieve equilibrium state during the consequent 5s hold period), at least 5s relax time should be maintained. Secondly, the Z-axis moving unit was controlled persistently upward at the velocity of 5mm/s up to 25% engineering strain and stop data acquisition. The sequence was repeated 6 times. Between each test, the remaining tissues and glue were removed. Generally, 3 ex-vivo porcine brains were used to measure the relationship of engineering stress and strain.

![Figure 2. The schematic of experimental setup.](image)

### RESULTS

Six tests on cylindrical samples were performed at the velocity of 5mm/s up to 30% strain in compression and tension in order to ensure the soft tissue in the elastic deformation range. The effects of sample’s damage were reduced in a simultaneous tension compression test. Force-displacement data was collected directly at a sampling frequency of 100Hz, which were converted to engineering stress-strain curve. Due to the brain is regarded as incompressible material, the change of contact area was not overlooked. The Euler’s stress was adopted to accurately express the relation of volume and area.
\[ \lambda = \frac{L}{L_0} \]  
\[ \sigma = \frac{F}{A} = \frac{F}{A_0} \lambda \]  
\[ \varepsilon = \frac{L-L_0}{L_0} \]

Where \( \lambda \) is stretch ratio and \( L \) is ultimate length. The \( L_0 \) is initial length. \( A \) and \( A_0 \) are loading area and initial area, respectively. The \( F \) is total load. Figure 3 shows the engineering stress with the strain at the range of -35% and 25%. The Young’s modulus of brain in compression is higher than tension. The three order polynomial was processed by MATLAB to fit the experiments data. The \( \gamma^2 \) values are up to 98.50%, which shown the polynomial model is reliable and trustworthy. As shown in Table 1.

\[ \sigma = \sum_{i=1}^{k} C_i \varepsilon^i \]  
\[ \sigma = 25794 \varepsilon^3 - 14848 \varepsilon^2 + 12958 \varepsilon \]  
\(-0.35 < \varepsilon < 0.25\)

<table>
<thead>
<tr>
<th>Constant Coefficient</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
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<tr>
<td>Numerical Values</td>
<td>12958</td>
<td>-14848</td>
<td>25794</td>
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**CONCLUSIONS**

The goal of this test is researching the instantaneous elastic response under compression and tension. According to the curve of engineering stress-strain, the finding that brain is elastic should be reliable and practical. The coefficients of the instantaneous elastic response in compression and tension were investigated by MATLAB. Conclusions are obtained as following:

In compression and tensile test, the stress almost increase linearly with the increment of strain at the velocity of 5 mm/s. The one linear polynomial and second terms polynomial can fit the engineering stress-strain curve. Because of the viscoelastic mechanical properties of brain, second order polynomial more appropriate to characterize the instantaneous elastic response. It provides a parameterized equation to define elastic response, which may be adopted in LS-DYNA. Due to a limitation of assuming isotropy of the tissue, while the brain
tissue exhibit anisotropy of behavior. Further work will focus on the other regions to accurately the elastic property.

ACKNOWLEDGEMENT

The financial support of the National Natural Science Foundation of China is gratefully acknowledged. The authors thank Dr. J Zhou for very helpful discussions. (Grant No. 51375268)

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