Biomechanical Analysis of CNS Gray Matter in Tension and Compression

Sina Mehdizadeh[i], Siamak Najarian[ii *], Farhad Farmanzad[iii] and Mehdi Khoshgoftar[iv]

ABSTRACT

The purpose of this study is to survey cross section changes of the animal brain samples during the tension and compression tests and comparison of the experimental results for three animals: bovine, sheep, and rabbit. A linear elastic theory with considering the necking in tension and barreling in compression has been considered for brain tissue. Bridgman method for tension and cross section updating method (using a picture analyzing through a computer program to trace cross section changes during the test) for compression has been applied in order to consider necking and barreling. It is shown that the effect of cross section changes of the samples during the test is not negligible. Differences in the behavior of brain tissue of bovine, sheep, and rabbit in both compression and tension are discussed. Results are in good agreement with previous works in the literature.

KEYWORDS

Biomechanics, Brain Tissue, Mechanical Behavior, Tension, Compression

1. INTRODUCTION

Mechanical modeling of brain tissue is important because it has a substantial number of applications in robotic surgery, surgeon training systems, and traumatic brain injury simulation as well as in modeling of hydrocephalus and designing of helmet [1-3]. More than 35 years passes from initial efforts to determine brain tissue mechanical characteristics [4]. Until 1970 only a few papers were published on mechanical properties of the brain tissue [5], but just recently several groups have focused on structural properties of the brain tissue and different biomechanical models of brain tissue have been proposed. A wide range of models in the literature is due to numerous factors involved in the deformation of the brain in various circumstances.

Reported mechanical properties of brain tissue vary more than one order of magnitude. Existence of this scatter could be due to the fact that several issues such as differences in testing procedure, different donor species (e.g., age, tissue region and orientation), post-mortem conditions may affect determining brain tissue characteristics.

Mechanical characteristics of brain tissue have been analyzed *in vitro* and in compression [6,7], tension [8], and shear by linear and/or nonlinear elastic, poroelastic or viscoelastic models [9,10,11,12].

Typically, animal brain tissues are used in experiments. In a research, a linear viscoelastic model was proposed for brain tissue that could explain the behavior of the brain tissue in lower strain rates in compression (e.g., surgery). In that study, experiments were conducted on swine brain tissue [13]. In another study, isotropic hyperelastic models were used for describing brain tissue behavior. Relevant experiments were conducted in tension on porcine brain matter. In a recent study, a biphasic model based on experiments on human brain tissue was proposed for brain tissue [14].

All materials in tension test, after a meaningful time from beginning of the experiment, undergo necking phenomenon, but in tension mode of brain tissue, owing

---

i S. Mehdizadeh is with the Faculty of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: s.mehdizadeh@aut.ac.ir).

ii * Corresponding Author, S. Najarian is with the Faculty of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: najarian@aut.ac.ir).

iii F. Farmanzad is with the Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran (e-mail: f.farmanzad@sazeh.co.ir).

iv M. Khoshgoftar is with the Faculty of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran (e-mail: p.khoshgoftar.eng@gmail.com).

to the flexibility of tissue, necking starts from beginning of the experiment. Since necking disrupts steady manner of uniaxial stress, standard equation of stress and strain cannot be applied. In view of this, equations for post-necking have been created [15,16]. In addition, in compression test, buckling of the specimen during which the cross section of the specimen increases during the test, also occurs. It seems that in performing tension and compression test on brain samples, cross section changes of the samples during the test would not be negligible and will affect the results. Since accurate models are needed for various applications introduced for mechanical modeling of brain tissue, it is worthwhile to consider cross section changes of the samples during the tests.

In this study, for the first time, in order to survey cross section changes of the samples during the tests, a linear elastic theory with Bridgman method in tension and area correction method have been applied for brain tissue. Differences in the behavior of brain tissue of the mentioned animals in tension and compression are discussed. Results are in good agreement with previous works in the literature. It is also shown that the effect of cross section changes of the samples during the test is not negligible.

2. MATERIALS AND METHODS

A. Experiment

Experiments were conducted on three animals: bovine, sheep, and rabbit. Information related to sample preparation, experimental condition, experimental setup, placing of the samples, loading history, and recording are as follows:

Sample Preparation: Grey matter samples were harvested from parietal lobe. Surgical scalpel was applied for cutting the samples. Dimensions of the samples were as follows:

- o Samples were harvested from bovine and sheep tissues: cylindrical disks with 15 millimeters in diameter and 5 millimeters in height.

- o Samples were harvested from rabbit tissue: cylindrical disks with 15 millimeters in diameter and 3 millimeters in height.

It is of importance to denote that because of the adhesive nature of brain tissue, cutting samples with accurate dimensions is difficult and it needs high accuracy through cutting.

Experimental Condition: Experiments were conducted in less than 5 hours post-mortem. In order to simulate brain situation in CSF, samples were preserved in physiological saline before the start of the experiments. During the experiments, no signs of dehydration of samples were observed. Experiments were conducted at room temperature.

Experimental Setup: Experiment setup should be capable of working in different range of rates (in order to simulate strain rate at impact, surgery or quasi-static conditions) and capable of exact measurement of small vertical forces. As shown in Figure 1, the setup, which was applied in this study, had 0.01 N and 0.001 millimeter axial force resolution (Dynamic Testing Machine, Hct/25-400, Servo Hydraulic Valve PID Controller, Zwick/Roell Co., Germany) that uses Toolkit1998 software to acquire data. Figure 2 shows a photograph of the setup. Various parts are being shown in the same figure.

Placing of Samples: In tension test, clamps are usually used for placing of the samples in experimental setup. However, because of the nature of brain tissue, this may cause primary stress on the sample and subsequently error in the results. It has been proposed to use surgical adhesive to stick the sample to the setup. This method is suitable for minimizing the friction between sample and surface of the setup [12]. In this study, in both tension and compression tests, the upper and lower surfaces of the sample were stuck rigidly to the setup using a surgical adhesive called DERMABOND. This type of surgical adhesive does not penetrate in the tissue. During experiments, there was not any slippage of the sample.

Loading History: Constant displacement was applied in the experiments for loading. Loading for all running was displacement with the rate of 1 mm/min (0.017 mm/s). This amount of strain rate is convenient not to produce inertia forces on the sample [17].

Recording: Because of the nature of method used in this study (Bridgman method in tension), it was needed to know the change of the geometry of the samples during the test. Recording was done using a CCD camera (SONY, Japan). In order to analyze the pictures, they were taken on a black background.
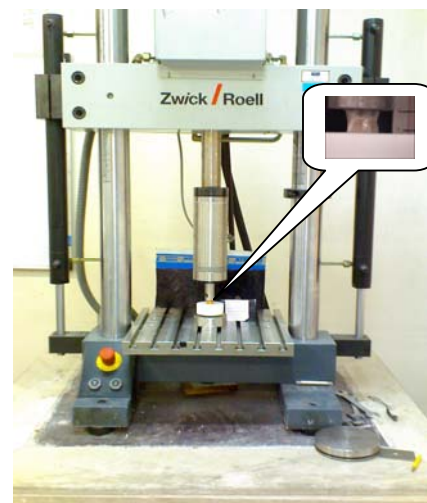

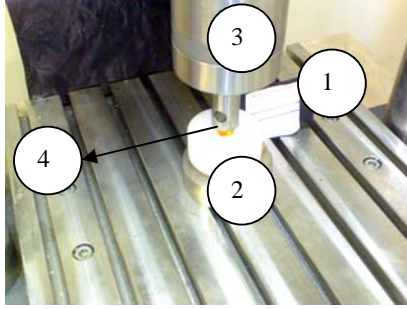Figure 1: Photograph of experimental setup.

Figure 2: Parts of experiment setup; 1: scale, 2: fixed fixture, 3: mobile fixture, 4: brain sample.

B. Theory

In tension of brain tissue, owing to flexibility of tissue, necking starts from the beginning of the experiment. Since necking disrupts steady manner of uniaxial stress, standard equation of stress and strain cannot be applied and to obtain more accurate results, it is necessary to consider changes in cross section directly in the formulation or update the cross section in formulation through picture analysis during the experiment. Here, a linear elastic theory with Bridgman method [16] in tension (using a picture analysis through a computer program) has been applied for brain tissue.

To consider cross section changes in theory, true strain can be defined as:

$$\varepsilon = \int_0^\varepsilon d\varepsilon = \int_{L_0}^{L_f} \frac{dL}{L} = \ln\frac{L_0}{L_f} \tag{1}$$

where L_0 is the initial length and L_f is the ultimate length of the sample. For true strain we have:

$$\varepsilon = \ln(1+e) \tag{2}$$

which e is the engineering strain.

To obtain true stresses in tension, the Bridgman method can be used. For a cylindrical beam, Bridgman hypothesized the followings (Figure 3):

1. Strain distribution in minimum area is uniform.

2. Beam's longitudinal gridline in necking zone changes to a curve with radius of curvature of $1/\rho$:

$$\frac{1}{\rho} = \frac{r}{aR} \tag{3}$$

3. Ratio of principal stresses remains constant.

As per the Bridgman method, the equivalent uniaxial

stress (the Bridgman stress) can be defined as a nominal stress $(\sigma_a)_{av}$ corrected with a coefficient k as follows:

$$\sigma_e = \frac{(\sigma_a)_{av}}{(1+\frac{2R}{a})\ln(1+\frac{a}{2R})} = k(\sigma_a)_{av} \tag{4}$$

where k is:

$$k = [(1+\frac{2R}{a})\ln(1+\frac{a}{2R})]^{-1} \tag{5}$$

Finally, average stress can be defined as:

$$\sigma_{ave} = 1/2(\sigma_{ini} + \sigma_e) \tag{6}$$

where σ_{ini} is the stress at sample' initial cross section.
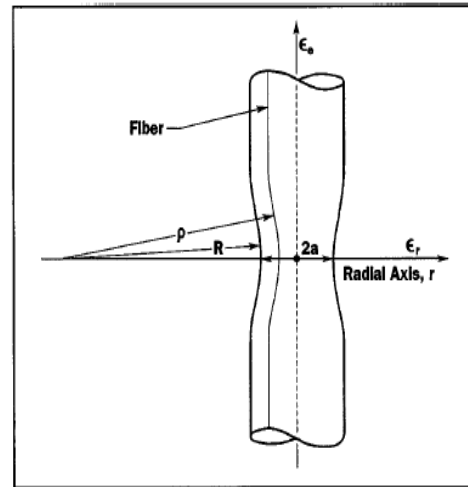

Figure 3: Schematic view of necking zone.

In the compression test, the true cross section area is the cross section area of the buckling section $A_{True} = A_{Max}$. In order to obtain true stress, force is divided by true cross section area.

$$\sigma_{True} = \frac{F}{A_{True}} \tag{7}$$

Finally, average stress which is the average of true and engineering stresses is calculated by equation (8):

$$\sigma_{ave} = 1/2(\frac{F}{A_{Max}} + \frac{F}{A_0}) \tag{8}$$

For analyzing the pictures to trace cross section changes during the test, we prepared a computer program (we named it the Brain Test) written in visual FoxPro. For each experiment, 10 pictures were taken to compute their geometrical information. First, a picture was imported to

the program. In each process, for a picture, the scale pixels were converted to 10 millimeter length (scale's length). Then, both the diameter of the sample a and the radius of the curvature ρ at necking zone were calculated. For computing the radius of curvature, a circle was drawn along the curvature of the sample with applying 3 points. The program running can be seen in Figure 4.
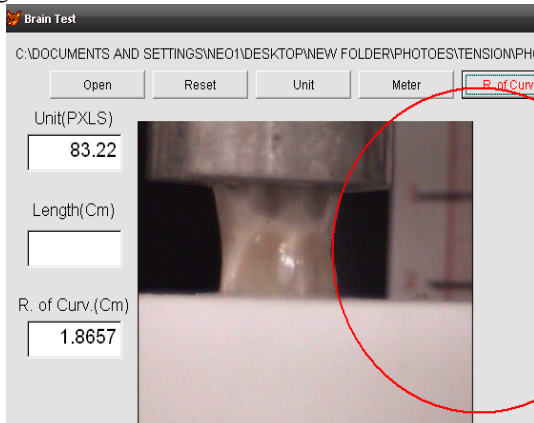

Figure 4: Brain Test program running, written in visual FoxPro for analyzing the pictures to trace cross section changes during the test.

3. RESULT AND DISCUSSION

After conducting the experiments, load-displacement curves obtained from setup data were converted to the true stress-strain curves. For each experiment, two curves were plotted. Segmented line indicates the nominal stress-strain (load divided by initial cross section) and continued line is the average stress-strain curve calculated from Equation (7) for tension (Figure 5).

As can be seen in Figure 5, in compression, sample cross section increases with time and therefore true curves have a lower slope than the nominal one. This means that in compression, the true Young's modulus is less than the nominal Young's modulus. In addition, in tension, sample cross section decreases with time and therefore true curves have a higher slope than the nominal one. This means that in tension, the true Young's modulus is greater than the nominal Young's modulus.

In Table 1, the results have been summarized. According to the data of Table 1, in tension, the Young's modulus measured for different animals are different. The bovine brain tissue has the highest Young's modulus.

Table 1: Samples' Young moduli..

Type of Animal	Average Young's Modulus (kPa)	
	Tension	Compression
Bovine	24.6	55.8
Sheep	17.9	168.8
Rabbit	3.8	168.9

From the data of the table three primary results are obtained:

A: tissue stiffness is different in tension and compression.

B: in tension test, the bovine brain tissue has the maximum Young's modulus while in compression rabbits and sheep brain tissue are three times stiffer than bovine's one.

C: in all test the stiffness of brain tissue in compression is more than in tension. This is due to the contained CNS in the brain tissue which is incompressible.

According to Table 1, the sheep with Young modulus of 168.8 kPa and rabbit with Young modulus of 168.9 have similar Young moduli in compression.

Besides, in tension, the value of 24.6 kPa for Young's modulus of bovine brain tissue has been accessed. For the sheep's brain tissue, this value is 17.9 kPa which is close to the range of 10.2-11.8 kPa which was estimated for human brain tissue in a recent study based on brain microstructural characteristics [19]. It is also close to the value of 11 kPa for the human brain tissue introduced in a study based on the deformation of the brain ventricles due to the epidural hematoma by applying a FEM model and thereby estimating brain tissue's Young modulus that agreed with the reality [1]. In the case of rabbit, the value of 3.8 kPa has been accessed for Young's modulus. This value matches the value of 3.2 kPa introduced for swine brain tissue [20].

Another issue which can be extracting out of the results is that for strains lower than 10%, considering a linear elastic theory is acceptable for modeling the brain tissue. This conclusion is also in agreement with the literature.

In Table 2, the error in nominal values in comparison with true values of Young's modulus has been presented. Mean difference between nominal values and true values of Young's modulus is 10% in tension and 24.4% in compression. This amount of difference is substantial and it seems it should be considered in the brain modeling. These errors are because of necking in tension and are unavoidable.

Table 2: Error related to nominal values compared with true values.

Animal	Error (%)	
	Tension	Compression
Bovine	11.7	18.5
Sheep	7.8	41.7
Rabbit	10.5	13

4. CONCLUSION

In order to survey the effect of cross section changes of the samples during the tension tests of brain tissue, a linear elastic theory with the Bridgman method in tension and area correction in compression were applied in this study. To obtain a more comprehensive view, experiments

were conducted on three animals: bovine, sheep, and rabbit. Differences in the behavior of brain tissue of the mentioned animals in tension and compression are discussed. It is shown that differences between true and nominal values are not negligible. That is the effect of cross section changes of the samples during the test cannot be ignored.

5. ACKNOWLEDGMENT

a1

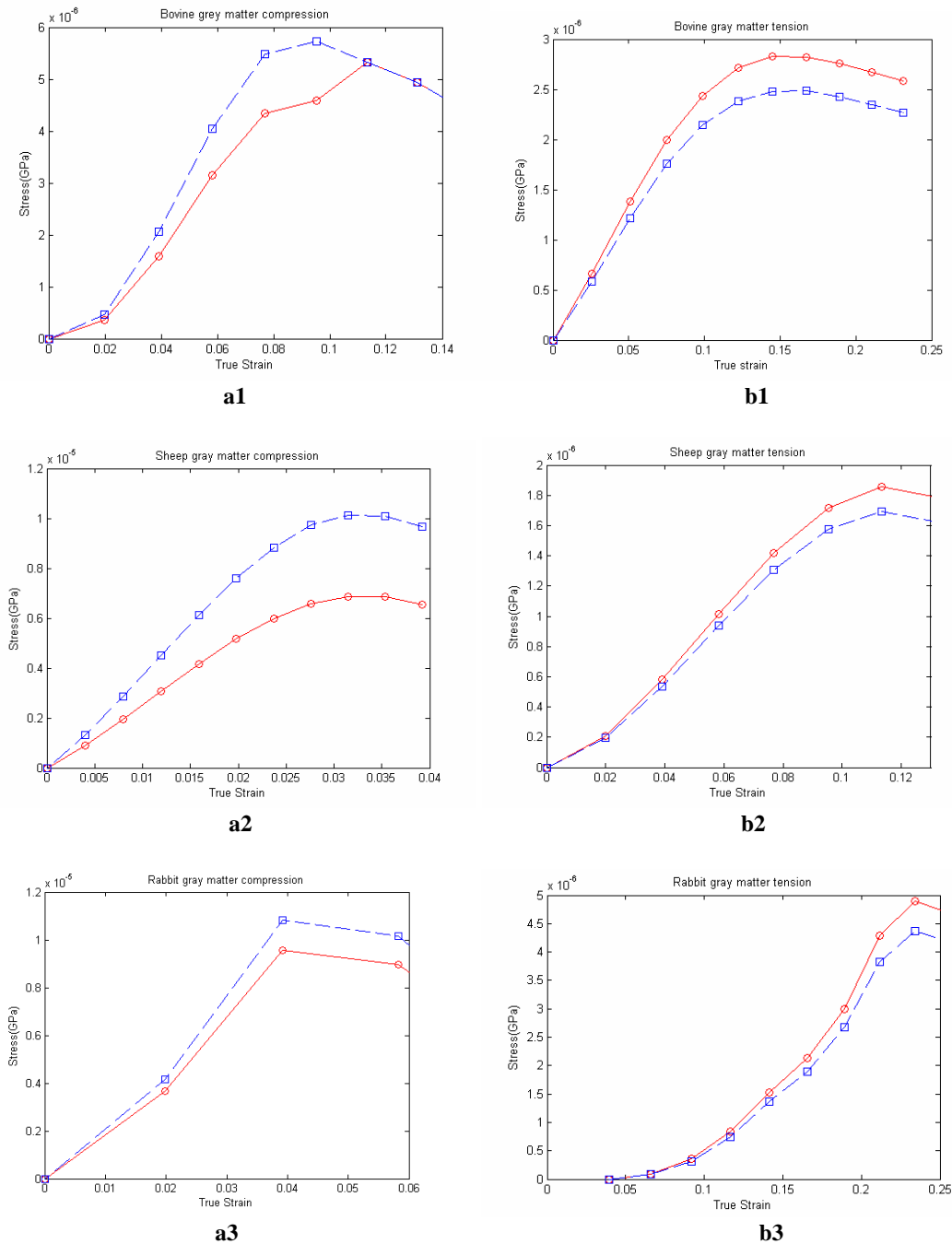**b1**

a2

b2

a3

b3

Figure 5: Stress-strain curves in tension for (a) tension and (b) compression for (1) bovine, (2) sheep, and (3) rabbit. Segmented line indicates nominal stress-strain (load divided by initial cross section) and continuous line is the average stress-strain curve calculated.

6. REFERENCES

[1] Farmanzad, F.; Najarian, S.; Eslami, M.; Seddighi, A.S.; "A novel model for biomechanical behavior of human brain in epidural hematoma injuries", Bio-Med. Mater. and Eng., vol. 17 (2), p.p. 119-125, 2007.

[2] Pott, P.P.; Scharf, H.P.; Schwarz, M.L.R.; "Today's state of the art surgical robotics", J. of Comput. Aid. Surg., vol. 10 (2), p.p. 101-132, 2005.

[3] Taylor, Z.; Miller, K.; "Reassessment of brain elasticity for analysis of biomechanics of hydrocephalus", J. of Biomech. Eng., vol. 37, p.p. 1263-1269, 2005.

[4] Walsh, E.K.; Schettini, A.; "Elastic behavior of brain tissue in vivo", Am. J. Physiol., vol. 230, p.p. 1058-1062, 1976.

[5] Ommaya, A.K.; "Mechanical properties of tissues of the nervous system", J. of Biomech., vol. 1, p.p. 127, 1968.

[6] Estes, M.S.; McElhaney, J.H.; "Response of brain tissue of compressive loading", ASME Pub., 70-BHF-13, 4, 1970.

[7] Miller, K.; "Constitutive modeling of brain tissue: Experiment and theory", J. of Biomech., vol. 30, p.p. 1115-1121, 1997.

[8] Miller, K.; Chinzei, K.; "Mechanical properties of brain tissue in tension", J. of Biomech., vol 35, p.p. 483-490, 2002.

[9] Bilston, L.E.; Liu, Z.; Phan-Thien, N.; "Large strain behavior of brain tissue in shear: Some experimental data and differential constitutive model", Biorheolog, vol. 38, p.p. 335-345, 2001.

[10] Brands, D.W.A.; Bovendeerd, P.H.M.; Peters, G.W.M.; Wismans, J.S.H.M.; "The large shear strain dynamic behavior of in-vitro porcine brain tissue and the silicone gel model material", Proc. of the 44th Stapp Car Crash Conf., 2000-01-SC17, p.p. 249-260, 2000.

[11] Donnely, B.R.; Medige, J.; "Shear properties of human brain tissue", J. of Biomech. Engin., vol. 119, p.p. 423-432, 1997.

[12] Prange, M.T.; Margulies, S.S.; "Regional, directional, and age-dependent properties of the brain undergoing large deformation", J. of Biomech. Eng., vol. 124, p.p. 244-252, 2002.

[13] Miller, K.; "Constitutive model of brain tissue suitable for finite element analysis of surgical procedures", J. of Biomech., vol. 32, p.p. 531-537, 1999.

[14] Franceschini, G.; Bigoni, D.; Regitni, P.; Holzapfel, G.A.; "Brain tissue deforms similarly to filled elastomers and follows consolidation theory", J. of the Mech. and Physics of Solids, vol. 54: p.p. 2592–2620, 2006.

[15] Hashemi, J.; Bennettv, R.; "Materials Characterization: Tensile Test", Mater. and Mech. Laborat., ME 3328, 2003.

[16] Ling, Y.; "Uniaxial True Stress-Strain after Necking", AMP J. of Technolog., vol. 5,1996.

[17] Velardi, F.; Fraternali, F.; Angelillo, M.; "Anisotropic constitutive equations and experimental tensile behavior of brain tissue", Biomech. Model Mechanbiol., vol. 5, p.p. 53–61, 2006.

[18] Mendis, K.K.; Stalnaker, R.L.; Advani, S.H.; "A constitutive relationship for large deformation finite element modelling of brain tissue", J. of Biomech. Eng., vol. 117, p.p. 279–285, 1995.

[19] Khoshgoftar, M.; Najarian, S.; Farmanzad, F.; "A Biomechanical Composite Model to Determine Effective Elastic Moduli of the CNS Gray Matter", Am. J. of Appl. Sci., vol. 4, p.p. 918-924, 2007.

[20] Miller, K.; Chinzei, K.; Orssengo, G.; Bednarz, P.; "Mechanical properties of brain tissue in vivo: experiment and computer simulation", J. of Biomech., vol. 33, p.p. 1369-1376, 2000.