FINITE ELEMENT MODEL OF ELECTRODE SHAFT INSERTION INTO BRAIN TISSUE

[1]FARIS TARLOCHAN, [2]SIVA MAHESH TANGATOORU

[1,2]Department of Mechanical and Industrial Engineering, Qatar University, Qatar
E-mail: [1]faris.tarlochan@qu.edu.qa

Abstract- Surgical simulation is a growing field of interest as it serves as a good training for the medical practitioners as well as planning and preparing for surgery. For a reliable and a good outcome from the simulation, the challenge is to model the material properties of tissues as accurate as possible. For a real time surgical simulation the numerical model has to be simple and computationally inexpensive. One of the preferred numerical models is the finite element model. Hence, the objective of this paper is to present findings of stresses on brain tissue due to specific strain rates of electrode insertion.

Keywords- Brain tissue stress, Finite Element, Strain rate, Electrode shaft

I. INTRODUCTION

Interactive and real time surgical simulation is a very important tool in today's health care industry [1 - 5]. Latest technology has reduced to less invasive surgeries by the surgeons. This is accomplished by smaller cuts during surgery. This results in loss of direct contact and tactile information to the surgeons. As a result, surgeons need to adapt themselves to improve their hand-eye coordination. Here simulation tools such as finite element models can to some extend accurately predict tissue injuries. This is also useful for surgeons to practice and plan their surgeries [6-8].

The motivation for this work is related to an ongoing research onto addressing the high incidence of blindness in eastern Arabia. Glaucoma is the major ophthalmological challenge for the eastern Arabian population. Glaucoma destroys retinal ganglion cells, the neurons which connect the eye to the visual brain. Without these cells visual signals cannot reach those parts of the central nervous system that give rise to perceptions. Since human ganglion cells do not grown anew and once lost are gone forever, the only practical means of restoring vision to those blinded through glaucoma is a neuroprostheses that interfaces visual neurons of the brain to stimulating electrodes driven by an image capture system and electronic circuitry. This involves navigating the electrodes and penetrating the brain tissue to reach the target side. Hence one of the objectives is to study the level of tissue injury by means of the penetrating electrode. This will help in planning the trajectory for the invasion. Hence a finite element model to study this.

II. FINITE ELEMENT MODELDEVELOPMENT

2.1. Brain Material Model

The main key in developing brain tissue finite element material model is the level of accuracy needed. There is a paradox here where the surgical simulation of tissues has to be simple to be used for a broad range of medical conditions but with sufficient complexity to realistically describe the accurate physical response due to variety of applied loading conditions. The review of various material models will help in identifying a solution for this paradox.

Linear Elastic Models

Linear elastic models are commonly used in most finite element analysis as it is the easiest to be implemented in terms of computational time and setting the model up. Several researchers have developed linear elastic model for measuring brain deformation [9 – 12]. From [12], it was found that for a strain rate of 0.01 s-1 (quasi static testing) of actual brain tissue, the tissue can be approximated with a linear elastic model provided the strain does not exit 10%. Higher strain values will significantly differ between the linear model and the observe experimentation data. Even though the brain tissue can be approximated with linear elastic model, however from a clinical point of view this is not really good since most surgical procedures involve deformations of more than 10% [12].

Hyperelastic Models

Hyperelastic material model is used to describe the non-linear stress-strain behavior of complex materials such as tissues. The model assumes that the material behavior can be described by means of a strain energy density function, from which the stress–strain relationships can be derived. Hyperelastic materials can be considered to be isotropic, incompressible and strain rate independent. Due to the large deformations seen on tissues during surgeries, these models are used extensively for all kinds of tissues such as brain [13, 18], liver tissue [14], skin [15], soft tissues [16] and for general laparoscopic simulation [17]. The relevant equations of the strain energy function can be explained as follows [18]:

Hyperfoam function:

$$U = \sum_{i=1}^{N}\left[\frac{2\mu_i}{\alpha_i^2}\left(\varphi_1^{\alpha_i} + \varphi_2^{\alpha_i} + \varphi_3^{\alpha_i} - 3\right) + \frac{1}{\beta_i}\left(J^{-\alpha_i\beta_i} - 1\right)\right] \quad (1)$$

Where □i are the principal stretches: J is the determinant of the deformation gradient tensor; N is the number of terms; and□□□□□□□□□□□are material parameters.

Ogden Strain Energy Potential:

$$U = \sum_{i=1}^{N}\frac{2\mu_i}{\alpha_i^2}\left(\bar{\varphi}_1^{\alpha_i} + \bar{\varphi}_2^{\alpha_i} + \bar{\varphi}_3^{\alpha_i} - 3\right) + \sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i} \quad (2)$$

Where □i are the deviatoric principal stretches, D are material parameters.

Polynomial Strain Energy Potential:

$$U = \sum_{i+j=1}^{N} C_{ij}(I_1 - 3)^i(I_2 - 3)^j + \sum_{i=1}^{N}\frac{1}{D_i}(J-1)^{2i} \quad (3)$$

Where C_{ij} are material parameters and I_1 and I_2 are the first and second deviatoric strain invariants.

From the study conducted by Moran et al [18], it was found that the Hyperfoam, Ogden and polynomial functions have relatively good fit to the experimental data. The coefficient of determination for the Hyperfoam, Ogden and Polynomial were 0.97, 0.92 and 0.80 respectively. In order to achieve a good fit, a value of N = 2 had to be used to avoid strain softening. For each of the above functions the Poisson's ratio were 0.38, 0.42 and 0.44 respectively. Hyperfoam model was the best amongst the three models for the compression test. In terms of shear test, the polynomial function did not fare as well. Tables 1-3 show the parameters for all the three models obtained from [18].

Viscoelastic Models

The coupling of elasticity and viscosity creates a viscoelastic material with specific mechanical responses and it needs specific experimental investigations and modeling approaches. Viscoelastic materials are materials where the stress and strain depends on time or, in the frequency domain, on frequency. Polymers are good example of viscoelastic materials. Several researchers have used linear viscoelastic models to model the brain tissue [19]. This model has also been used by other researchers to model other tissues such as liver [20 -21] and joints [22]. Some have used this for surgical simulation purpose [23, 24].

For the brain tissue, it is not very accurately to represent them as linear viscoelastic. To some extend brain tissues are non-linear viscoelastic [12]. Several researchers have worked in this aspect to develop non-linear viscoelastic material model for finite element application [25, 26]. Even though the nonlinear viscoelastic model is a good representation of the brain tissue, it is difficult to estimate the parameter values for the model and can be computationally expensive [27]. Some researchers tried to improve the linear viscoelastic model by introducing quasi-linear viscoelastic viscoelasticity [12]. Here the tissue is assumed to have two material behavior: a time dependent elastic response and a linear viscoelastic stress relaxation response. It was found that this model fits experimental behavior accurately up to strains of 15%, a much better improvement than the linear elastic models.

Table1: Parameters for Hyperfoam [18]

Brain Tissue Region	Mu 1 (Pa)	Alpha 1	Mu 2 (Pa)	Alpha 2	β_1, β_2	G (Pa)	R^2 Compression	R^2 Tension	R^2 Shear
White matter	67.19	10.65	981.67	-3.45	9.15, 1.57	1048	0.97	0.98	0.98
Gray matter	76.46	10.96	1267.70	-3.20	11.70, 0.89	1344	0.97	0.98	1.00
Corona radiata	75.50	11.63	1359.40	-3.84	12.00, 0.72	1434	0.97	0.98	1.00

Table 2: Parameters for Ogden [18]

Brain Tissue Region	Mu 1 (Pa)	Alpha 1	Mu 2 (Pa)	Alpha 2	D_1, D_2	G (Pa)	R^2 Compression	R^2 Tension	R^2 Shear
White matter	71.33	11.61	826.35	-6.07	3.13E-04, 4.98E-04	897	0.99	0.98	0.99
Gray matter	116.43	7.49	1058.9	-6.75	3.19E-04, 3.89E-04	1175	0.98	0.96	0.99
Corona radiata	90.94	6.97	1150.6	-7.42	3.18E-04, 2.62E-04	1241	0.98	0.92	0.99

Table 3: Parameters for Polynomial Function [18]

Brain Tissue Region	C10 (Pa)	C01 (Pa)	C20	C11	C02	D_1, D_2	G (Pa)	R^2 Comp.	R^2 Tension	R^2 Shear
White matter	-1455	2186	3235	-5276	1875	3.13E-04, 0.00	1462	1.00	0.95	0.98
Gray matter	-1526	2291	3226	-5276	1958	3.13E-04, 0.00	1530	0.99	0.95	0.89
Corona radiata	-1545	2372	3123	-5146	2052	3.13E-04, 0.00	1653	0.99	0.91	0.80

From published experimental data, the mechanical response of brain tissue to external loading is very complex. The response is non-linear where brain tissue has a higher stiffness in compression than in tension. Three types of common brain tissue material models used in finite element analysis were discussed; namely the linear elastic, hyperelastic and viscoelastic. The linear elastic model is the simplest and computationally fast. However, this model is only accurate for strains up to 10%. From these three models, the hyperelastic model, represents accurately the tissue behavior up to strains of 50% [12]. Quasi-linear viscoelastic models are good for strains up to 15%. Hence, it can be concluded here that defining the elastic response of the brain tissue is best done with the hyperelastic material model.

2.2. Finite Element Model

The finite element analysis was done by using ABAQUS/Explicit. Since the electrode shaft dimensions are very small with respect to the overall human brain dimension, the human brain tissue will be modeled by using a cuboid of dimensions 50 mm x 50 mm x 50 mm. The electrode shaft will be modeled using a thin shell with three different diameters, 2 mm, 1 mm and 0.5 mm. The finite element model is shown in Figure 1.

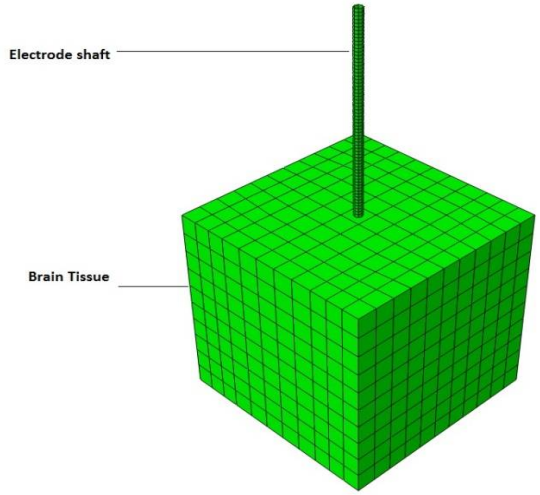


Fig.1. Finite element model

The electrode material was based on DBS Lead Model 3387. The electrode shaft was modeled as shell elements (S4R). An element size of 0.8 mm was used for the electrode shaft. Since the shaft is more rigid than the brain tissue, linear elastic model was assumed for the shaft.For the brain tissue, linear hexahedral elements (C3D8R) were used with an element size of 5 mm.

The material was modeled using the Ogden hyperelastic parameters as depicted in Table 2. The electrode shaft was assigned different insertion velocities to develop the following strain rate effects: 0.5 s^{-1}, 1s^{-1}, 2s^{-1}, 10s^{-1} and 20s^{-1}. The brain tissue was also assigned a pin boundary condition to allow some rotations to mimic the physical response of the brain. Finite element simulations were carried out to study the effect of shaft diameter and insertion speeds on the stresses developed on the brain tissue.

III. RESULTS AND DISCUSSION

3.1. Effect of shaft diameter

Figure 2 depicts the typical stress contours seen on the brain tissue due to the various shaft diameters. The stress was normalized with respect to the stress generated by the lowest strain rate. The results are depicted in Table 4. It can be seen from Table 4 that the change in shaft diameter has insignificant effects on the stress. This is probably due to the fact that the size of the electrode is small compared to the brain tissue. Hence the stress is localized.

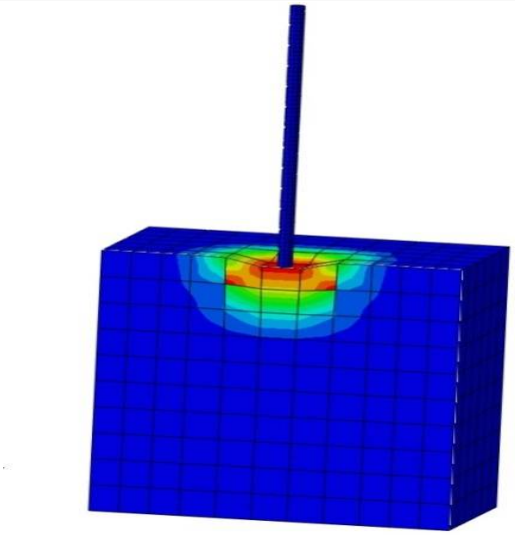


Fig.2. Stress on brain tissue at location of electrode insertion

Table 4. Stress Normalization

D 2 mm			
	Strain rate	Sigma (Pa)	Normalization
	0.5	44	1.0
	1	91	2.1
	2	192	4.4
	10	1775	40.3
	20	8723	198.3
D 1 mm			
	Strain rate	Sigma (Pa)	Normalization
	0.5	46	1.0
	1	93	2.1
	2	194	4.4
	10	1779	40.4
	20	8727	198.3
D 0.5 mm			
	Strain rate	Sigma (Pa)	Normalization
	0.5	47	1.1
	1	94	2.1
	2	197	4.5
	10	1812	41.2
	20	8734	198.5

3.2. Effect of Strain Rate

As it can be seen from Table 4 and Figure 3, the strain rate due to different insertion speeds on the electrode has significant effects onto the brain tissue. This finding is important as it indicates that strain rate beyond 2.5 s^{-1}, multiplies the stress in the brain tissue by nearly 4 folds.

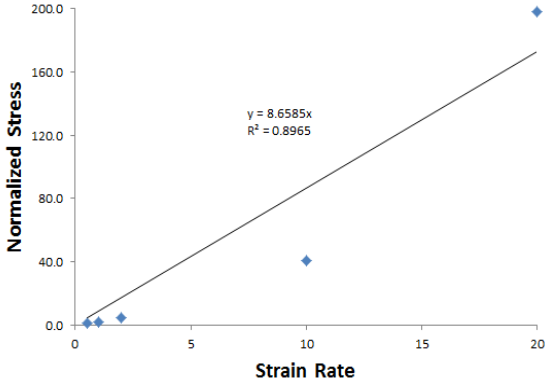


Fig.3. Strain rate effects on normalized stress

CONCLUSIONS

A study based on finite element simulations was done to understand the effect of electrode shaft diameters and insertion speed on stress generated in the brain tissue. The following are the findings:

1. The electrode shaft diameter has negligible effect on the magnitude of stress in the brain tissue.
2. Electrode shaft insertion speeds beyond 2.5 s^{-1} increases the stress in the brain tissue by 4 folds.

This is an initial study to understand the physics of electrode shaft insertion into the brain tissue. Further work is needed to refine the accuracy and to study multiple nano electrode insertion for the creation on the neuroprostheses.

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