

Computational Analysis of Surgical Tool-Brain Tissue Interaction

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Abstract
This paper presents new surgical tool-brain tissue interactions models in three directional format considering the linear elastic, hyperelastic and viscoelastic properties of a brain tissue which are characterized by conducting stress-strain simulation on brain model. Brain tissues properties like a Neo-Hookean, Mooney-Rivlin Model and Prony Series are considered. Effects of adopting non-linear properties are discussed. After optimizing models in COMSOL Muiltiphysics 4.0, the models show that the brain tissues contain non-linear characteristic and the coefficients of the models are available to Open Inventor in order to initiate a visio-haptic simulation which will be used for doctors and surgical operation manipulators.

INTRODUCTION

Brain edema is a foremost common consequence of serious traumatic brain injuries which usually caused by increase in the intracranial pressure due to increase in the brain fluid content (Li G. X et al 2009). Brain tumor is considered to be the most widespread disease of all the brain injuries cases. Reports have shown that up to 10% of the population of the developed cities are expected to develop one brain problem or another in their lifetime (Humphrey at al 2008). Brain surgery has since being a major problem to a surgeon because many lives usually lost during the operation and hospitalization time is usually longer than necessary.

Since the world is combating with high rate of brain tumor, proper monitoring and detection of the state of the brain treatment becomes an important procedure. Brain tissue imaging is a one of the major potential means of addressing the needs of brain tumor screening and diagnosis. (Miller K et al. 2010) developed a computer-integrated surgery in order to guide the medical personnel's for non-invasive operation of brain tissues. In order to investigate the hardware, software and computational performance of the sensor on soft tissues, compressions or tensile experiments were carried out. Computer-based brain simulation system that makes use of Virtual Reality (VR) technique is a promising alternative to traditional trainings in medical fields. Surgical simulation system helps the medical doctors to touch, feel, and manipulate the organs involved with the same set of medical materials used in minimally invasive surgery while viewing images of the tool-tissue interactions on a monitor as in real procedures.

Over the past a decade, pre-planning and surgical simulation system became a major alternative to surgeon before operations, researchers have demonstrated an advancement in the use of real-time brain surgical simulation system and high-fidelity to create simulation of medical operations that are very important in the present society and the future. Most of the researchers agree that surgical simulation systems provide a safe environment, accurate and effective method for surgical training for neurological surgeons before operation and as well in planning for robotic-assisted surgery, effective surgical tool development and modern knowledge of tissue and tools interaction which are the major requirements for the development of real-time surgical simulation system (Misra et al 2002, 2008a & De et al 2007).

FINITE ELEMENT ANALYSIS

According to Ogden (1984), he describes finite element technique as the theory and principle of deformation of continuous materials under the action of shear forces and is usually called continuum mechanics. In his work, the continuum mechanics (models) is illustrated by the relationship between the four major mechanical parameters: displacement, strain, stress and force. Displacement is the movement of particles in the continuum. Movement changes the parameters of small volume element, and these can be measured using strain deformation tensors. These strain deformation tensors can them express the elongation, shear forces and other parameters of the volume elements. Forces appear to be the same as displacements, in that they are applied to particles of the continuum. To measure their effect on volume elements, the stress tensor is used. Forces and displacements are external factors that can be observed while strain and stress are internal mathematical parameters to measure the effects of displacements and forces respectively on the modelled soft tissues (Ogden 1984). The relationships between stress and strain determine the actual physical deformation behaviour of the continuum. Non-linearity occurs both between displacement and strain, and strain and stress. To solve this problem of non-linearity of elasticity and viscous fluid mechanics is to simplify the internal mechanical properties of the tissues. These simplifications are basically implemented using Taylor series, and only valid for small deformable materials. (Mistra et al 2008a).

M. Bro-Nielsen (1998) suggest a better performance models for elasticity-based mechanical property of soft tissues and tool interaction which offer by the use of finite element method, this model contribute greatly to development of real-time and accurate surgical simulation system. Many researchers have proposed the model to be more reliable and high accuracy (Miller et al 2010, Miller K 1999, 2002, Wittek et al 2004 and Misra et al 2008b). This model is made up of a defined mesh over a set of nodes which described the geometry design of the soft tissues and its boundary conditions over the mesh approximately the real deformation theory. Finite element elastic model provide a solutions to the geometry difficulties because its mesh geometry provide a direct computation of the element parameters. Finite element approach consider the mass-spring models as a linear form, it obtains its model by computing spring and nodal parameters. (Cotin et al 1996).

Many researchers have reported that the equations of field of the continuous material are normally created by the tensors (Mistra et al 2008b, Miller 2005, Wittek et al 2004 and Christensen et al 1993). They argue that variations in the geometry conditions of the tool create changes in the force (stress)-deflection behaviour only for non-linear elasticity-based (large deformable) material.

Most of their modelling and reports are based on invasive or non-invasive techniques but they are from one of the following finite element analysis categories.

a. Linear Elastic Finite Element Models
b. Hyperelastic Finite Element models
c. Viscoelastic Finite Element models

LINEAR ELASTIC FINITE ELEMENT ANALYSIS

This describes the modelling of the tool-organ interaction using linear elastic finite element technique without rupture (Misra et al 2010). This technique is mostly applied to model human tissues deformation in Neurosurgery simulation system by most researchers because of its simplicity and computational accuracy which enable real time rendering. (Bro-Nielsen et al 1998 & Misra et al 2010).

NON LINEAR FINITE ELEMENT ANALYSIS

The characteristics of soft tissue are regarded as nonhomogeneous, anisotropic in nature and nonlinear. Fung (1993) illustrated the mechanical characteristic of tissues by considering the stress–strain relationship for different tissues. However, tissues generally made up of elastin and collagen materials.

MODELING SETUP

A Solid, plain stress-strain and Poisson's equation are coupled for modeling the brain tissue in COMSOL Multiphysics platform. A two dimensional model of brain tissue was developed and computational analysis was carried out to determine the corresponding mechanical loading force response and effect of introducing of notching in form of uniaxial indentation on the skull model before applying the loading force. Models deformation and stress tensor experienced was computed with the use of COMSOL Multiphysics platform. The geometrical information of the brain model consists of the cerebral cortex, Spinal cord, neck, thalamus, medulla oblongata, artery, hard skull. Also, the surgical tool was also introduced as a solid structure material model.

Due to symmetry, only one-quarter of the brain geometry was designed for the study, this reduces the size of the model as well the time for the simulation. The application of a one-quarter part of brain model is discretized to keep the computation time low. The setup chosen for modelling is the geometry branching with tissues placed at the branching site. Shape, position, and setup of the brain tissues are incorporated into the models and the changes in brain tissues response to the external load (loading force) in form of pressure are investigated. Since the material constituents in the cerebral cortex differs from both the arterial wall and the skull as described by MacDonald et al (2000). Different materials and properties are employed for each domain used for their mechanical properties.

In this case, it is important to assume the force that must be applied in order to place the surgical tool in the human brain, which was placed as 10[N/m]. From a numerical point of view, this is a highly nonlinear structural analysis, mainly due to the contact interaction between the brain and the surgical tool (copper), also due to the non-linearity constitutive law selected for the brain tissue and finally due to the geometrical nonlinearity originating from the large deformation.

The process of modeling in COMSOL Multiphysics involves the following steps:

- geometry design (what phenomena are studying),
- definition of the materials properties involved in the geometry
- boundary condition to connect the physics to the geometry
- meshing the appropriate domain parameters
- Solving the modeling with different solvers as well as post-process (parameters to visualize) the results.

BOUNDARY CONDITIONS

It is necessary to apply different material properties to all subdomains. The material of the model is divided into three mechanism- Linear Elastic material model, Viscoelastic material model and hyperelastic material model.

However, the model is divided into the following subdomains - the cerebral cortex domain, the Spinal cord domain, the neck domain, the artery domain, the thalamus domain, the medulla oblongata domain, artery, the hard skull domain and the surgical tools subdomain. The cerebral cortex subdomain is modelled as a Neo-Hookean viscoelastic material because it exhibit both viscous and elastic characteristics when undergoing deformation. The Spinal cord subdomain is modelled as a Mooney-Rivlin hyperelastic material because it experiences recoverable large elastic strain whereas the skull subdomain was modelled as a pure linear elastic material model (Neo-Hookean). The Thalamus and neck subdomains were also placed on Viscoelastic material also. The other subdomain (Artery, medulla Oblongata and the surgical tool) were subjected to linear elastic materials.

The Neo-Hoookean viscoelasticity based material is described according to the strain-energy function

$$W = C_{10}(I_1 - 3) \qquad \text{………………………………………………} \qquad 1$$

The only material parameter included in the Neo-Hookean strain-energy function is the shear modulus G and the only variable that is used is I_1 which is the first principal invariant of the right Cauchy-Green strain tensor.
The Mooney-Rivlin hyperelastic material is described by the strain-energy function.

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \qquad \text{…………………………………………} \qquad 2$$

This strain-energy function uses two material parameters c_1 and c_2 and includes two principal invariants I_1 and I_2 as variables. The increased number of material parameters and variables allows for a more precise and accurate material response that will resemble that of brain tissue given the correct material parameters. The downside to this improvement in material response is an increase in computational time used by the finite element model solver. The combination of the two differentiated material subdomains should therefore result in a detailed material response of the brain tissue subdomain while the simplification of the material model in the arterial subdomain should keep computation time by the finite element model solver at a minimum.

The whole parts of the model were conditioned in all directions. The skull is placed to accept the external force for the model, since we adopt a symmetry modelling, the symmetry parts is constrained for the function. However, the neck was roller constrained, force load was applied along the skull interface. To account for the material properties dependency of brain tissues, the mechanical properties of the brain are assumed to be isotropic and homogenous.

For the brain model, assume a viscoelastic material model with isotropic hardening and a constant young's modulus, with material parameters according to the following table1.

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Table 1: *Detailed presentation of the materials properties*

Subdomain	**Parameter**	**Value**	**Reference**
Cerebral Cortex	Module Large Deformations Material Model Initial Shear Modulus Initial Bulk Modulus Density	Structural Mechanics Module – Solid Stress-Strain On Viscoelastic Neo-Hookean G=6.20E6 [N/m^2] κ=1.24E8 [N/m^2] ρ=960 [Kg/m^3]	Kock S et al (2009)
Artery	Module Large Deformations Material Model Initial Shear Modulus Initial Bulk Modulus Density	Structural Mechanics Module – Solid Stress-Strain On Hyperelastic Neo-Hookean G=6204106[N/m^2] κ=20[GN/m^2] ρ=960[Kg/m^3]	Rasmussen J et al (2009)
Skull	Module Large Deformation Material Model Young's Modulus Poisson' Ratio Density	Structural Mechanics Module-Solid Stress-Strain On Viscoelastic (Neo-Hookean) E=11.9[kN/m^2] v=0.49 ρ =1180[kg/m^3]	Khoshgoftar M (2007)
Spinal Cord	Module Large deformations Material Model Density Material Parameter C_1 Material Parameter C_2	Structural Mechanics Module-Solid Stress-Strain On Hyperelastic (Mooney-Rivlin) ρ =960[kg/m^3] C1=15[N/cm^2] C2=4[N/cm^2]	Rasmussen J et al (2009)
Medulla Oblongata	Module Large Deformation Material Model Young's Modulus Poisson' Ratio Density	Structural Mechanics Module-Solid Stress-Strain On linearelastic (Neo-Hookean) E=9.010[kN/m^2] v=0.35 ρ =1200[kg/m^3]	Zarandi M M. et al (2010)
Thalamus	Module Large Deformations Material Model Initial Shear Modulus Initial Bulk Modulus Density	Structural Mechanics Module – Solid Stress-Strain On linear elastic Neo-Hookean G=943[GN/m2] κ=20 [GPa] ρ=960[Kg/m^3]	Dommelen J.A.W. van (2010)
Neck	Module Large Deformation Material Model Young's Modulus Poisson' Ratio Density	Structural Mechanics Module-Solid Stress-Strain On Linear elastic (Neo-Hookean) E=9.010E3[N/m^2] v=0.42 ρ =1060[kg/m^3]	Li X. G et al (2009)
Surgical tool (Copper)	Module Large Deformation Material Model Young's Modulus Poisson' Ratio Reference permittivity Heat Capacity at pressure Reference resistivity	Structural Mechanics Module-Solid Stress-Strain On Linear elastic model E=110e9[Pa] Nu=0.35 epsilonr =1 Cp=385[J/kg*K] Rho0=172e-8[ohm*m]	COMSOL MUILTIPHYSICS Module

***Table 2**: Summary of the model meshing properties built in the study*

	Case 1	Case 2
Number of hexahedral element meshing	7430	3437
Number of tetrahedral element meshing	1002	1245
Number of points	49	53
No of Subdomain	15	11
Number of degrees of freedom	33711	14313
Time taken for the computation (s)	16	7
Total number of boundaries involves	60	57

SIMULATION OF BRAIN MODEL

In any surgical operation, surgical tools apply forces on the brain tissue, which brings deformation on the tissues. However, such situations are simulated using constant force of 10N/m in form of pressure to the selected nodes on. The response of each point (node) to the applied constant forces was the computational reaction forces simulated between the brain model and the surgical tool. Only one quarter of the brain was modeled for simulation as the symmetry was assumed. In order to prevent motion of the model, the cerebellum, neck model and the skull were highly constrained as described in the boundary settings.

The duration for the simulation on a personal computer of Intel ® core™ 2 duo CPU 2.20 GHz processor, Window 7 and 32-bit Operating system and 2.00 GB of internal Memory was 36s for case1 model and 20s for the case 2 model. That shows that the time required for the operation of the notched is shorter than the without notch. However, it will be reasonable to expect that the simulation time will be reduced by applying computer with higher processors which will not only improve the efficiency but also increase the integration time of the continuum mechanics equations. Using the higher technology system and improved computer hardware, the simulated and computational duration can be reduced as well as enhanced better accuracy which is necessary in real-time surgery.

Finally, employing the general principle of physics in biomedicine is challenging yet extremely accurate and precise in carry out analysis. Often many kinds of physics will coalesce and interact to produce systems of partial differential equations of quite formidable proportions, and modelling mechanical characteristic phenomena is a very heavy yet at the same time often extremely intuitive way to build a practical knowledge in physics. It is of great value to not only be able to formulate the problem in terms of partial differential equations, but also to actually be able to solve the problems and visualize the results in a clear and straightforward manner, and COMSOL Muiltiphysics is certainly not only valuable, but quite essential in making the Biomechanics and Simulation possible for analysis.

The models used in the analysis consist of the viscoelastic, hyperelastic as well as linear elastic material. The results are being useful in approximate modelling the behaviour of the brain tissue model, which includes its material properties for accurate computation in robotic manipulation. The major reason of the brain model used in the work is the constitutive equation modelled which is already available in COMSOL Multiphysics 4.1 and can be implemented for large-scale analysis.

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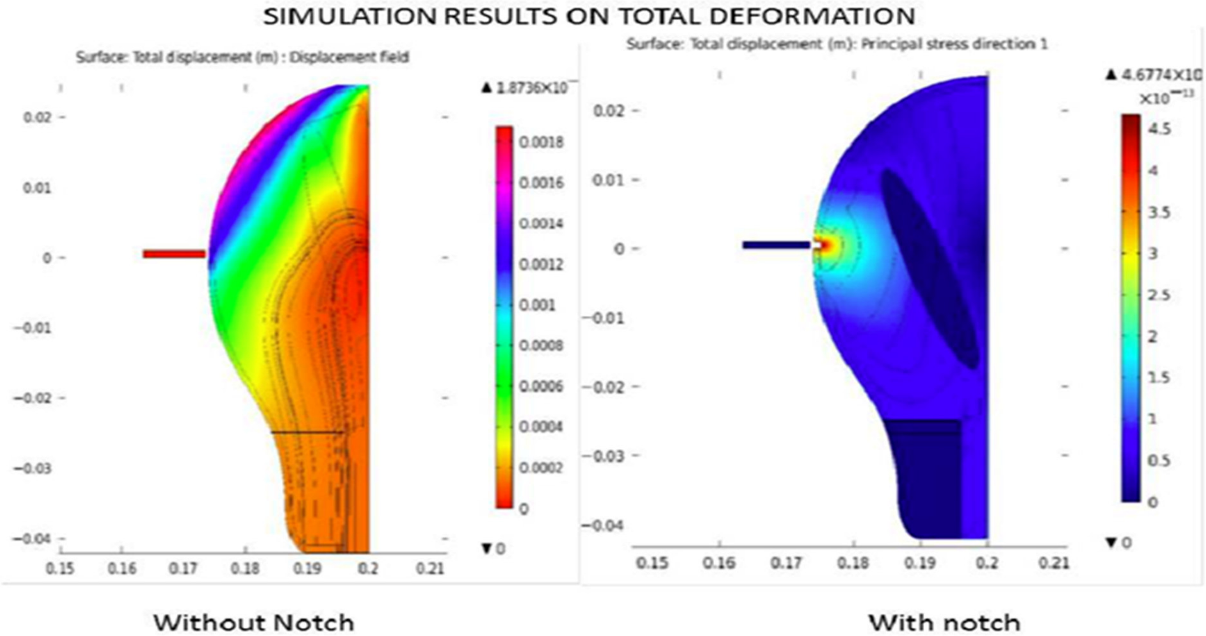
Table 3*: The Simulation results of both Total displacement and Stress tensor computed at each point. Case one shows the result for model without indentation while the case 2 present the result of the indented model.*



	SIMULATION RESULT OF BRAIN MODEL										
Point	1	2	3	4	5	6	7	8	9	10	11
Total Displacement (m)	0	0	0	0	1.91E-04	1.91E-04	1.32E-04	1.32E-04	1.31E-04	1.29E-04	1.32E-04
Stress tensor (N/m^2)	0	0	0	0	-0.0011	-0.0012	0.0656	0.4175	0.5056	0.9595	0.1672

12	13	14	15	16	17	18	19	20	21	22	23
1.31E-04	1.29E-04	1.29E-04	1.31E-04	1.31E-04	0.0012	1.92E-04	1.92E-04	1.51E-04	1.48E-04	1.32E-04	0.0014
0.5967	0.9972	0.3404	0.2325	0.4832	-4.568	0.0327	0.0804	0.0119	-0.0089	0.1191	12.8622

24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
0.001	1.91E-04	1.90E-04	1.51E-04	1.48E-04	1.33E-04	4.79E-04	2.09E-04	1.84E-04	2.00E-04	9.48E-04	1.76E-04	2.18E-04	1.30E-04	1.29E-04
-4.906	0.3178	0.3056	0.0053	-0.0044	0.4036	-11.8903	-5.9701	-5.5892	-6.3085	-11.1985	-5.9313	-8.1732	1.096	1.0962

39	40	41	42	43	44	45	46	47	48	49
1.29E-04	1.28E-04	1.29E-04	1.54E-04	5.26E-05	9.47E-05	1.23E-04	9.26E-05	3.89E-06	1.83E-05	0
1.0837	1.0672	1.1108	-11.0728	-0.3965	0.4439	-0.1102	-0.1592	-4.5687	-4.3615	-5.1341

CONCLUSION

In this work, a simple model has been developed for analysing a deformation and stress tensor experience by the brain tissue during surgical operation. The relationship of the tool and tissue is compared with the same model information and contents of brain properties but different means of introduction of force for with or without indentation was presented using combination of purely linear elastic hyperelactic, viscoelastic material for brain model. Modelling and accurate simulation of brain materials are a rather complex task. For a better description of the stimulation effects, not only inhomogeneity and anisotropy, but also the complex properties of the brain tissue and mechanical processes have to be taken into account. This is an important result that allows using biomechanical models for accurate analysis of properties of the brain tissue.

The deformation of the brain model has major impact on the stress tensor levels imposed on the real brain tissue. Computational analyses provide an accurate and precise information concerning brain tissues when undergoing external stress which may help the surgical robotic engineer to design a manipulator for neurosurgeon devices in order to solve the current methods of diagnostics.

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