Construction of Physics-Based Atlas and its application in Brain Deformation Analysis

A. Roy*, W. L. Nowinski, F. E. H. Tay

Department Mechanical Engineering, National University of Singapore,

Singapore 119260

E-mail: avijit@nus.edu.sg

Abstract. Physics-based modeling provides a powerful tool for investigating the biomechanics of soft tissue deformation incorporated with knowledge of mechanical properties using appropriate boundary conditions. We have developed a physics-based atlas model with detailed anatomical information based on Cerefy Brain Atlas. A nonlinear hyper-viscoelastic mechanical property typically suited for neurosurgery simulation has been incorporated. This model accounts well for brain tissue deformation during neurosurgical procedures (strain rate between 0.001s⁻¹ – 1.0s⁻¹). It is able to simulate the deformation for the entire brain and individual sub-cortical structures as well. The limiting stress relaxation for an infinitesimally small loading has also been obtained (shear modulus reaching 194.62 Pa) exhibiting similarity with a hydrocephalic condition.

1. Background

Today physics-based (PB) techniques provide a powerful tool for investigating the biomechanics of brain deformation particularly when used in conjunction with experimental studies. In opposed to purely geometric models, physics-based models incorporate additional constraints (such as material properties) that are very useful in accurate modeling and simulation. Several models have been reported for fast computation and mechanical deformation of soft tissue. Some of them were non-physical in nature while many others are physics-based. Terzopoulos first introduced such physically based modeling for the simulation of deformable objects. One of the most widely used physical methods has been the spring–mass model that represented a system consisting of various nodes connected by elastic links. However these types of models do not incorporate real material parameters and hence are very weekly related to the physical biomechanical behavior of soft tissues. Most recent PB models have applied Finite Element Method (FEM) – a numerical solution technique that has already shown great power and promise for the solution of differential equations in solid mechanics. However, most FE brain models, even today are being built considering as homogeneous, linear elastic bodies; and in many occasion the complex geometric information of the brain is much simplified hence restricting the realistic representation of the brain. In addition, most of the previous research into the mechanical properties of the brain and the brain tissue was motivated by traumatic injury prevention, e.g. fall, sports, automotive accident etc. which require investigation of very fast strain rate. Very less effort has been provided so far for closer

* Corresponding author; Tel: +65-6478 8415, Fax: +65 6478 9048

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examination of mechanical properties of brain tissue at moderate and low strain rates, which are relevant to surgical procedures.

In this paper we have proposed a FE brain model with detailed anatomy derived from an anatomical atlas, Cerefy\textsuperscript{21,22} with a hyper-viscoelastic material property which typically suites neurosurgery simulations\textsuperscript{17,18,19}. FEM Brain model has been developed based on the assumption of large deformation of non-linear hyper viscoelastic material with quasi-static behavior\textsuperscript{17,18,20}. A nearly incompressible material behavior has been assumed for the brain tissue as the bulk modulus of brain has been found about $10^6$ times higher than the shear modulus.\textsuperscript{16} 10-node parabolic elements have been used in tetrahedral mesh generation as they yield better mathematical approximations and better curved boundaries compared to linear ones. The key advantage of the model is it is constructed based on detailed multiple sub-cortical structure that preserve salient anatomical information and it employs a non-linear hyperviscoelastic material property of the brain tissue typically suited for surgery simulation. The model can be extended to investigate various structural diseases such as hydrocephalus or tumor growth and results of treatment such as brain shift due to resection and tumor shrinkage due to radiotherapy.

2. Cerefy Brain Atlas as a Source of Anatomic and Geometric Information for Biomechanical Model of the Brain

The Cerefy Brain Atlas is arguably one of the best atlases available\textsuperscript{20, 22} and it has been chosen to develop our brain model on the account of its use in neuroradiology, clinical, research, educational practice and its commercial usage\textsuperscript{7,18,21,22}. This database contains multiple, complementary brain atlases with gross anatomy, brain connections, subcortical structures, and sulcal patterns. For the purpose of this work the Talairach-Tournoux (TT) brain atlas\textsuperscript{23} containing the gross anatomy is used though our approach is also applicable to the other atlases.

Because the Cerefy Brain Atlas is fully colored and labeled, the feature points (a set of point database describing the outlines or surface features of an object) of each structure were easily extracted. For example, the RGB value of the corpus callosum has been denoted by number: (130, 75, 130); putamen: (0, 135, 91); hippocampus: (179, 147, 179); caudate nucleus: (255, 239, 0) etc. The surface features of 43 structures were extracted from the images (bitmaps) of 27 axial plates separated about 2-5 mm vertically from each other. The feature points of the individual structures have been extracted to form point clouds (a set of three-dimensional points in 3D CAD) shown in Fig. 2. The surface models were constructed in a CAD platform from these point clouds. The model was then filled with solid tetrahedrons and prepared for Finite Element Analysis. The typical flowchart is as follows: Bitmaps $\rightarrow$ 2D feature points $\rightarrow$ Point clouds $\rightarrow$ Surface mesh $\rightarrow$ Volumetric mesh.

3. Biomechanical Model and Mesh Generation

The model was created using a SolidWorks\textsuperscript{TM} tool called loft. Loft uses cross sections to extrapolate along a curve. It lets user to create complex 3D shapes by interpolating multiple 2D cross-sections of various size. Loft connectors define how models profiles align. Construction of 3D model of some deep structures such as putamen (Fig. 1a) or hippocampus was straight forward and easy, while constructing some other parts complex sub-structures such as corpus callosum (Fig. 1b) or caudate nucleus needed some extra effort for having concavity and convexities along axial plane. We had to construct those structures gradually breaking into several steps, piece by piece.

The automatic mesher in COSMOSWorks\textsuperscript{TM} (later uploaded in ANSYS) has been used to generate a mesh based on a global element size, tolerance and local mesh control specifications. Two key points were considered while meshing. First, geometric features must not prevent the mesh from being created and must also contain surfaces of consistent size and shape ratios to prevent forcing high aspect ratio and/or transitions between edges that may comprise accuracy.
Generally a good rule of thumb for minimizing occurrence of high aspect ratio elements is to limit transitions of 2:1 or less, if geometry is broken into patches. Secondly, simplification or manipulation of features in an attempt to clean up geometry would not reduce structural integrity of the part. In the early stages of design a larger element size was specified for a faster solution. Later, for a more accurate solution, a smaller element size was chosen. Mesh was generated by 10 node 3D parabolic tetrahedral solid elements (SOLID187). The entire brain model (surface area: 82170.56 mm²) consists of 15452 elements with 23461 numbers of nodes (element size: 6.1691mm, tolerance: .03085). Fig. 2. shows the volumetric mesh of the constructed model.

Figure 1. Construction of a) putamen b) hippocampus c) caudate nucleus d) corpus callosum using loft technique.

Figure 2. 3D model of brain : (a) volumetric mesh of the brain with caudate nucleus, (b) meshed model showing tetrahedrons.

4. Application: Modeling of Brain Deformation

Physics-based application of our model in a scenario where uniform load at 0.5 mm per second indenter speed on the top surface of the brain (Area: 3784.34 square millimeters; Perimeter:
265.87mm) is simulated. The formulation of appropriate boundary conditions constitutes a significant problem in biomechanics of soft tissues\textsuperscript{20}. Here we tried to construct a hypothetical scenario from where one can study the brain tissue behavior in compression in moderate strain rate (strain rate between 0.001s\(^{-1}\) – 1.0s\(^{-1}\)) due to the forces acting on the top of the brain by the surgical tools. As a crude approximation, the brain is assumed to be submerged in CSF, thus its weight is considered to be neutralized by the buoyant force. It was also assumed that the bottom surface of the brain did not move, thus immovable (no translations) restraint has been set which confirms all translations on the specified plane to zero. A frictionless sliding between brain tissue and skull was considered for the upper half of the brain surface. The static displacement of the model has been illustrated in Fig. 3. The limiting case of the constitutive model can be determined. For instance, assuming \( t \rightarrow \infty \), the equilibrium elastic behavior can also be obtained. The shear modulus in undeformed state at infinitesimally small loading can be achieved approximately, \( \mu_\infty \equiv 194.62\text{Pa} \) that exhibits the similarity with hydrocephalus condition\textsuperscript{7}. Fig. 4(a) shows the predicted true stress for the elastic model with large deformation. The time dependent relaxation component infinitesimally small loading has been plotted in Fig.4(b).

Figure 3. (a) Complete brain model (b) Visualization of deformation after applying a uniform load

Fig. 4. (a) Plot of quasi static stress response, (b) Plot of Shear Modulus with time; In the limiting case the shear modulus at infinitesimally small loading reaches approximately, \( \mu_\infty = 194.62\text{Pa} \).

5. Conclusion

In this paper we proposed a FE brain model with detailed anatomy derived from an anatomical atlas, Cerefy. However, an accurate solution of the model needs the accurate biomechanical material properties of tissues of each structure to be known, which still falls under active area of research. For physical investigation of tissue properties, we have developed a system to test on an adult pig brain in Bioengineering Lab of National University of Singapore (NUS). We have also conducted a computer simulation of the effects of tumor growth and demonstrated the deformation of brain for the pore pressure distribution in meshed atlas. In addition, several novel solutions to analyze structural diseases such as hydrocephalus, and Parkinson’s along with tactile feedback system have been introduced for various atlas-assisted applications\textsuperscript{17,18,21,22}.
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