Modelling of the human brain with detailed anatomy for numerical simulation of surgical interventions

Chunping Gao\textsuperscript{1,2}, Francis Eng Hock Tay\textsuperscript{1}, Wieslaw L. Nowinski\textsuperscript{2}

\textsuperscript{1} Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576

\textsuperscript{2} Biomedical Imaging Lab, Agency for Science, Technology and Research, Singapore, 30 Biopolis Street, Singapore 138671
cgao@nus.edu.sg

Abstract. During the design and simulation process of MEMS medical devices used in neurosurgery, there is a need to build a brain model with detailed anatomy and physical properties incorporated as a platform to conduct numerical analysis. This paper presents a study on constructing a brain model for simulation of medical device interventions during neurosurgery. A brain atlas was utilized to develop a detailed model consisting of multiple structures. Two types of atlas model were generated employing different mesh types and biomechanical properties suited for various applications. The developed model was able to capture the detailed anatomy of the brain and reflect the application-dependant biomechanical behaviour based on material modelling of brain tissue under surgical intervention.

1. Introduction

Advancement in microelectromechanical systems (MEMS) processing technology have continually improved the functional capabilities of medical devices used in neurosurgery while reducing their sizes. During the design and simulation process of the MEMS systems used in neurosurgery, such as Ventriculoperitoneal (V-P) shunting systems, implantable microelectrode for treating Parkinson’s disease ([1], [2],[3]), there is a need to build a brain model that can account for the detailed brain anatomy and biomechanical properties incorporated as a platform to perform numerical analysis, e.g. Finite Element Analysis (FEA). To account for the complex and intricate nature of the human brain anatomy, brain atlases are frequently consulted in various applications of neurosurgery, neuroradiology, human brain mapping and medical education. In the past decades, there have been extensive studies on building comprehensive models based on brain atlases with detailed descriptions of gross anatomy, brain connections, subcortical structures, and sulcal patterns ([4], [5]). However, as these existing atlas models are based on geometric representation of the brain anatomy, they are not able to provide information of physical properties of brain, and thus cannot be directly used in many applications such as surgical numerical simulations where the physical response of the brain are required. This study aims to build a detailed Finite Element (FE) model of the human brain based on a brain atlas, to suit the applications of modelling and simulating medical device intervention in neurosurgery. By integrating the a-priori physics knowledge of brain, e.g. biomechanical and electromagnetic properties, with detailed anatomic information from brain atlases, this proposed
model may provide a new perspective and suggest possible solutions to some complex biomedical problems.

2. Materials and methods

For the purpose of building a generic FE brain model for various surgical scenarios, we constructed two types of brain models based on FEM which is recognized as a general numerical procedure in solving physical problems. Type one was for applications of small deformation analysis where the strain is less than 5%. The type two was applicable for a wider deformation range with a strain range up to 30% which is suitable for a variety of applications including neurosurgery simulation, biomechanics investigation of structural brain diseases. These two types of brain models were embedded with the same anatomical information obtained from the Cerefy Brain Atlas which is a digitalized and extended version of Talairach and Tournoux (TT) brain atlas [5]. The differences between the two models were mainly in the biomechanical modelling method in which the two models were incorporated with different material models to suit their respective application areas. The choice of finite element type and mesh topology also differed in order to accommodate the two typical application areas.

In the applications of small deformation, we have built a tetrahedral meshed brain model. We chose the digitized Talairach and Tournoux (TT) brain atlas containing gross anatomy as the source of anatomical information. A modified marching cube technique was implemented to obtain a 3D reconstruction of the atlas model [6]. A multi-object differentiation scheme was embedded during the process to segment the 44 structures of the brain. To convert the surface model into FEM compatible mesh, Delaunay triangulation in combination with element decimation and normalization were implemented to achieve high quality elements [7]. Because tetrahedral elements are recognized only suitable for small deformation cases [8], it is consistent to incorporate this tetrahedral model with linear elastic theory which takes the same assumption of small strain. Therefore the material property of this model was treated as linear elastic incompressible solid. The mechanical parameter Young's modulus were set as 2100 kPa, and Poisson ratio $\nu = 0.45$ as in consistence with previous work [9]. Some tetrahedral atlas meshes are shown in Fig. 1.

![Fig. 1. (a) Sub-cortical structures; (b) Corpus callosum; (c) Lateral ventricles; (d) Whole brain](image)

In the applications of larger deformation cases, tetrahedral mesh should be avoided because it introduces additional unnatural degree of constraints, resulting in a stiffer finite element mesh [10]. We then developed a hexahedral version of the FE brain model, consisting of all hexahedral elements which are particularly suitable for modelling incompressible materials like the brain tissue. An automatic hexahedral mesh generation algorithm was specifically developed to address the multiple-structure modelling of the brain atlas [11]. Due to the sparseness of brain atlas slices and the variable inter-slice distances, a weighted smoothing procedure in combination with an aspect ratio checking process was performed iteratively to guarantee the volumetric mesh quality. Salient features of the gross brain anatomy as well as the details of sub-cortical structures were preserved (Fig.2). By employing a multi-resolution sampling scheme, this mesh generation algorithm allows the control of
mesh density which is an important characteristic to guarantee convergence in finite element analysis. In addition to the capability to adapt to linear elastic material modelling, this hexahedral meshed model fulfilled the requirements of using a more complex and advanced nonlinear viscoelastic theory to model brain under large deformation. In the viscoelastic modelling of the brain tissue, the total tissue stress is assumed to consist of two components, i.e. an elastic or hyper-elastic component representing the instantaneous tissue response, and a viscous component representing the delayed tissue response. The nonlinear elastic part of this material is characterized in the Odgen form strain energy function. The viscous relaxation characteristic is modelled using a stress relaxation function based on Prony series.

The following Ogden-type form of the energy function for very soft biological tissues was used [12].

\[
W = \frac{2\mu_0}{\alpha} \int_0^\infty [\mu(t-t^*)] \frac{d}{dt} \left( \sum_{k=1}^n \left( \frac{t}{\tau_k} \right)^3 \right) dt
\]

(1)

The strain energy function is represented in the form of a convolution integral

\[
\mu = \mu_0 [1 - \sum_{k=1}^n g_k \left(1 - e^{-\frac{t}{\tau_k}}\right)]
\]

(2)

describes the relaxation of the shear modulus of the tissue. \(W\) is a potential function, \(\varepsilon^0\) are principal stretches, \(\mu_0\) is the instantaneous shear modulus in undeformed state, \(\tau_k\) is characteristic time, \(g_k\) are relaxation coefficients, and \(\alpha\) is a material coefficient, which can assume any real value without restrictions. The complete list of material constants for brain tissue is given in Table 1 in [13]. This model is suited for brain tissue behaviour in compression and extension for strains up to 30% and strain rates ranging over a few orders of magnitude, which includes the typical strain rate relevant to surgical procedures (0.01-1/s).

3. Results
The developed model consisted of 44 brain structures, including ventricles, corpus callosum, putamen, thalamus, etc. To validate the anatomical fidelity of the atlas mesh, both of the two types of models were compared with the original brain atlas slices. The modified Talairach landmarks [14] including the anterior commissure (AC) and posterior commissure (PC) in combination with feature points of structures were calculated and correlated (Fig.2, left). The results showed the anatomic features of the Cerefy brain atlas were well transcribed to the brain model with an error of 5%. As this paper is not aimed to give a quantitative study of the patient specificity and the case-dependent biomechanical modelling for a clinical application case, the validation of the general physical properties incorporated of the FE model is assumed to be provided by the biomechanical experimental research which they are originated from ([9], [13]). Some preliminary FE analysis results using a commercially available
package ABAQUS 6.4 (HKS Inc.) were shown in Fig. 3. The predicted deformation fields were in general consistence with previous work [15].

![Deformation Fields](image)

Fig. 3. (Up) Brain cortex and structure deformation under gravity (Down) Brain tissue under medical device intervention

4. Discussion and Conclusion
We presented in this article a new set of FE brain model with detailed anatomy from a brain atlas. Two typical types of physical atlas models in terms of topology and simulation applicability were developed with multiple-structure differentiation. The preliminary result demonstrated the developed model was able to capture the detailed anatomy of the brain atlas and reflect the application-dependant material properties based on the advanced biomechanical modelling of brain tissue. This model may extend the field of brain atlas applications to numerical simulation of surgery by introducing a-priori physics knowledge. As the research on biomechanics of brain has revealed that the characterization of brain material property at an anatomical structure level is necessary for realistic surgery or pathology simulations [16], with more intensive investigations of brain tissue physical properties, the combination of detailed anatomy with comprehensive physical properties can provide a new perspective to solve complex simulation problems of neurosurgical interventions.

References
[1] H. J. Yoon, J. M. Jung, J. S. Jeong, S. S. Yang, Micro devices for a cerebrospinal fluid (CSF) shunt system, Sensors and Actuators A, 110 (2004) 68
[2] T. Eggers, C. Marschner, U. Marschner, B. Clasbrummel, R. Laur, J. Binder, in: Proceedings of the IEEE MEMS Advanced Hybrid Integrated Low-Power Telemetric Pressure Monitoring System for Biomedical Applications, 2000, pp. 329–334.
[3] J. Subbaroyan, D. C. Martin and D. R. Kipke, A finite-element model of the mechanical effects of implantable microelectrodes in the cerebral cortex, J. Neural Eng. 2 (December 2005) 103-113 doi:10.1088/1741-2560/2/4/006
[4] W.L. Nowinski. Electronic Brain Atlases: Features and Applications. In: 3D Image Processing:
Techniques and Clinical Applications. Medical Radiology series (Springer-Verlag, 2002)

[5] J. Talairach, P. Tournoux, Co-Planar Stereotaxic Atlas of the Human Brain (Thieme, New York, 2003)

[6] W. E. Lorensen and H. E. Cline. Marching cubes: a high resolution 3D surface construction algorithm. In M. C. Stone, editor, Computer Graphics (SIGGRAPH '87 Proceedings), volume 21 (4), pages 163--170, July 1987.

[7] K. A. Ganser, H. Dickhaus, R. Metzner, CR. Wirtz, A deformable digital brain atlas system according to Talairach and Tournox Medical Image Analysis; vol 8; pp. 3-22; 2004

[8] T.J.R. Hughes, Talairach and Tournoxd Medical Image Analysis. (Englewood Cliffs, NJ: Prentice-Hall, 1987)

[9] M. I. Miga, K. D. Paulsen, F. E. Kennedy, P. J. Hoopes, A. Hartov, and D.W. Roberts, Modeling surgical loads to account for subsurface tissue deformation during stereotactic neurosurgery,” in IEEE SPIE Proceedings of Laser-Tissue Interaction IX, Part B: Soft-Tissue Modeling, vol. 3254, 1998, pp. 501–511.

[10] K.K. Mendis, R.L. Stalnaker, S.H. Advani, A constitutive relationship for large-deformation finite element modeling of brain tissue. J. Biomech Eng Trans ASME 117, 1995, 279-285

[11] C. Gao, F.E.H. Tay, and W.L. Nowinski, Proceeding of the Fourth IASTED International Conference Visualization, Imaging, and Image Processing (VIIP2004), 2004, pp 937-942

[12] K. Miller, Biomechanics of Brain for computer Integrated Surgery (Publishing House of Warsaw Univ. of Technology. 2002)

[13] K. Miller, and K. Chinzei, Mechanical Properties of Brain Tissue in Tension, J. Biomechanics, Vol 35/4, pp. 483-490, 2002

[14] W.L. Nowinski: Modified Talairach landmarks. Acta Neurochirurgica, 143(10); 2001; 1045-1057.

[15] O. Clatz, H. Delingueutte, et al. Patient-specific biomechanical model of the brain: application to Parkinson’s disease, IS4T Proc. 2003, 321-331

[16] M. Kaczmarek, R.P Subramanian, S.R. Neff: ‘The hydromechanics of hydrocephalus: steady-state solutions for cylindrical geometry’, Bull Math Biol 59, 1997, pp. 295-323