04-2903

Proceedings of the ASME 2007 Summer Bioengineering Conference (SBC2007)
June 20-24, Keystone Resort & Conference Center, Keystone, Colorado, USA

SBC2007-176670

IN VIVO TISSUE-LEVEL THRESHOLDS FOR SPINAL CORD INJURY

Jason Maikos, Ragi Elias, Zhen Qian, Dimitris Metaxas, David Shreiber

Rutgers, The State University
Department of Biomedical Engineering
Piscataway, NJ

INTRODUCTION

Traumatic loading conditions, such as those experienced during car accidents or falls, can lead to spinal cord injury (SCI), resulting in permanent functional damage [1]. A better understanding of the biomechanical causes of SCI and knowledge of the tolerance of spinal cord tissue to mechanical loading is critical in understanding how mechanisms of injury lead to neurologic deficits, as well as designing methods to prevent SCI. Finite element analysis (FEA) has become an important and cost effective tool to investigate the biomechanics of trauma. FEA has been used to study a variety of biomechanical analyses of trauma, including brain injury and spine injury biomechanics, but there have been limited analyses on spinal cord injury (SCI) [2-5]. In fact, despite the prevalence of small animal models in the neuroscience community used to study SCI, there have been no published analyses of in vivo models of SCI.

In this investigation, we developed and validated a computational 3D FE model of SCI using ABAQUS that simulates the Impactor weight drop experimental model. The FEM was validated against compression rate and compression depth data from our parallel Impactor weight drop experiments. The finite element analysis will provide temporal and spatial profiles of mechanical parameters that will be used to identify tissue-level thresholds for spinal cord microvascular injury. Moreover, the results will be used to improve means and measures of preventing spinal cord injury in humans.

METHODS

Mesh Generation

Spinal Cord Structures - An anatomically accurate mesh that includes the gray and white matter geometry was generated from MR images of rat spinal cord explants. A freshly excised, intact spinal column was placed in a 15ml conical tube with saline and inserted into a custom-built solenoid MR coil. The contents were imaged with spin-echo magnetization in a 4T magnet over ~3cm in length. Coronal images were segmented into gray and white matter and were blended into continuous surfaces with ProEngineer. The surfaces were converted to solids, partioned into uniform shapes, and meshed with 8 node hexahedron elements with Abaqus CAE. The cerebrospinal fluid (CSF) and dura were introduced by expanding the surface of the white matter 3% and 5% and again meshing with 8 node brick elements. The dura, CSF, and spinal cord were then merged together, while maintaining distinct boundaries.

Spinal Column - The geometry of the vertebral column was based on microCT imaging of a freshly excised spinal column. A T9/T10 laminectomy was performed in accordance with standard surgical procedures for the weight drop model of SCI, and the spinal column was removed and placed in a 15ml conical tube filled with saline. The column was imaged over 3cm in length. Image slices were thresholded into contours and generated into a mesh using Autodesk Maya software. The mesh was then imported into Abaqus and modeled as a discrete rigid body and fixed in space.

Material Properties–

Spinal Cord - The non-linear elastic properties of the spinal cord were defined with a one-term Ogden hyperelastic strain energy density function. The shear modulus for the spinal cord was modeled as 25kPa, alpha was set at 68.4, and Poisson's ratio was set at 0.45. The model was assumed to be homogeneous. The viscoelastic properties were taken from the literature [6].

Dura - The dura was modeled as a hyperelastic, linearly viscoelastic continuum solid. Experimental data was fit to the Ogden form of the hyperelastic strain energy potential function. The shear modulus for the dura was modeled as 875KPa, alpha was set at 14.9, and Poisson's ratio was set at 0.45. Time-dependent behavior of fresh rat spinal cord dura was analyzed with dynamic, uniaxial tension tests.

Viscoelastic time constants were determined by normalizing the relaxation portion of the stress vs. time curves and fitting the curves to a 2-term Prony series exponential decay.

CSF- The CSF was modeled as a Mooney-Rivlin hyperelastic material [7]. The shear modulus was chosen to be approximately 3 orders of magnitude less than the spinal cord.

Boundary Conditions

Contact was permitted between the impactor and dura, as well as between the dura and the spinal column. The spinal column was fixed in space. The impactor was permitted to move only in the vertical direction and allowed to have direct contact with the dura. The coefficient of friction for all contact interactions was estimated at 0.1.

Weight Drop Simulation

Impactor experiments were simulated using Abaqus Explicit by placing an analytical rigid surface in direct contact with the exposed surface of the spinal cord and prescribing gravitational force and the initial velocity of the impactor to match experiments (approximately 495mm/sec for a 12.5mm drop and 690mm/sec for a 25mm drop).

Validation

Our analysis was validated by comparing the compression rate and the displacement of the mass post-"impact" to the actual parameters measured during an Impactor weight drop. Parametric studies were performed to examine the effect of different parameters, such as the coefficient of friction, velocity, boundary conditions, and the material constants, on the FEM results. Simulations were run at +/- one standard deviation for each of the parameters, when available, or +/- 20% of the original value. A validated FEM will provide a description of the intraparenchymal distribution of stress and strain, which we will subsequently compare to the BSCB injury maps to determine thresholds for injury.

RESULTS

Mesh Generation

Coronal MR images of the rat spinal cord were segmented into gray and white matter and used to generate a finite element mesh (Fig 1). The mesh includes a finer mesh seed in the impacted region.

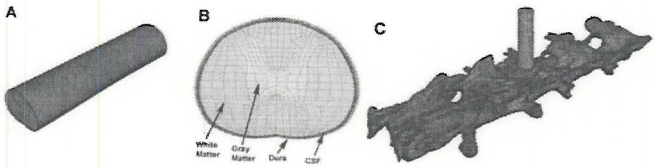

Figure 1 – Mesh of the spinal cord (A), a section of the spinal cord showing internal structures (B), and the spinal cord within the spinal column, with rigid impactor (C)

Validation

The FE analysis was validated by comparing the compression depth and rate to parallel Impactor experiments. Figure 2 shows the experimental Impactor experiments (gray) and the FEM (black) compression depths and rate. The model compression depth and rate were comparable to the experimental results.

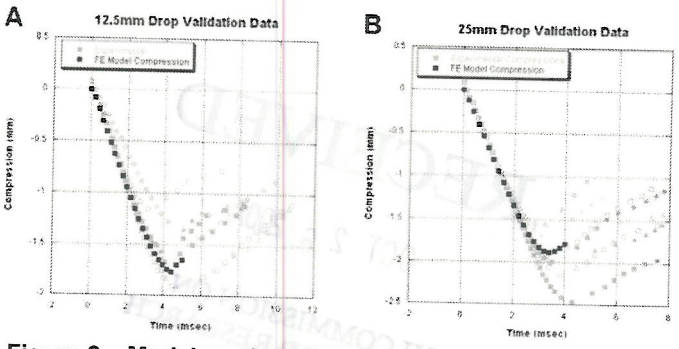

Figure 2 – Model prediction of impactor displacement falls in the range of experimentally determined displacement for both 12.5mm and 25mm weight drop experiments

Comparison to Experiments

Previous work in our laboratory has characterized the immediate changes in the blood-spinal cord barrier following weight drop injury. Results from the FEA match the distribution of extravasation of fluorescent tracers (Fig 3). Future work will entail quantitatively comparing the experimental and computational results with a logit analysis to establish thresholds for injury to the blood-spinal cord barrier.

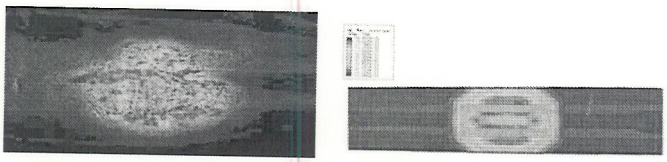

Figure 3 – Patterns of blood-spinal cord barrier injury correlate well to stress and strain patterns from the FEA

DISCUSSION

The long-term aim for this research is to link the patterns of SCI tissue-level states of mechanical stress and strain by simulating different models of SCI. Though injury may be induced by different means in different models, the relationship between primary injury patterns in these models and the 'internal', tissue-level stress and/or strain will be the same. We hope to determine this relationship by quantitatively comparing the results of the finite element model to the spatial profiles of primary injury following weight drop to predict threshold levels of stress and strain responsible for a given injury severity. These thresholds represent tissue-level targets for preventing SCI. Moreover, similarly modeling the mechanics of other models computationally will allow improved comparisons of results from laboratory-to-laboratory based on the internal, tissue-level criteria, and ultimately to improved standardization of injury patterns. Sponsored by the CDC (R49CCR 221744-01) and a fellowship from the NJ Commission on Spinal Cord Research.

REFERENCES

1. Mautes, A.E., et al., Phys Ther, 2000. **80**(7): p. 673-87.
2. Bain, A.C. and D.F. Meaney, J Biomech Eng, 2000. **122**(6): p. 615-22.
3. Shreiber, D.I., A. C. Bain, et al. SAE 1997 Transactions: Journal of Passenger Cars, 1997. **106(6-2)**:: p. 3792-3806.
4. Willinger, R., H.S. Kang, and B. Diaw, Ann Biomed Eng, 1999. **27**(3): p. 403-10.
5. Yoganandan, N., et al., J Biomech Eng, 1997. **119**(1): p. 87-92.
6. Fiford, R.J. and L.E. Bilston, J Biomech, 2005. **38**(7): p. 1509-15.
7. Mendis, K.K., R.L. Stalnaker, and S.H. Advani, J Biomech Eng, 1995. **117**(3): p. 279-85.