TISSUE LEVEL THRESHOLDS FOR SPINAL CORD INJURY (SCI) OF A RAT: AN EXPERIMENTAL AND NUMERICAL INVESTIGATION

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Introduction

Animal contusion injuries models have been shown to closely approximate Spinal Cord Injury (SCI) in humans [1, 2]. However, the underlying spinal cord biomechanics resulting from an impact causing permanent injury is not fully understood. In addition a full description of the hyperelastic and viscoelastic constants of the spinal cord is still missing in the literature [3]. To this aim, we have conducted an experimental and computational study to examine the severity and the extent of SCI in the rat following force-defined impact. Uniaxial tensile and compression tests on fresh spinal cord rat tissues were performed for the mechanical characterization of the spinal cord. Finite Element Analysis (FEA) from rat model were run to validate the experimental findings. Tissue strain was targeted for the assessment of thresholds for injury and compared with histological findings [4, 5]. We report that our FEM model enables predictions of injury extent and is a useful tool toward understanding the biomechanics of SCI.

Methods

A mild-to-moderate C4 midline SCI rat force controlled experiment was produced by the Infinite Horizon (IH) spinal impactor. Details of the experimental procedure have been presented in Zareen et al. (2017) [6]. Histological assessments of the lesion area were made using Hematoxylin and Eosin staining in all animals. Prior to the SCI procedure, a subset of animals were scanned using MRI (7.0 Tesla 70/30 Bruker Biospec, resolution 0.234 mm) to image soft tissues and microCT (Siemens Inveon, resolution 0.196 mm) to image bone. MRI and CT images were co-registered and a semi-manual segmentation was completed in ScanIP (Simpleware, Exeter, UK) for bone, dura mater, cerebral spinal fluid (CSF), white and gray matter. A C4 laminectomy was digitally obtained and the C2-C6 tract was cropped for the FEA (Figure 1). Uniaxial tensile and compression tests on fresh spinal cord rat tissues were performed to determine the hyperelastic and viscoelastic material constants of white and gray matter. Those constants were compared against the tissue material constants derived from curve fitting of stress-strain experimental data with different hyperelastic constitutive models (Figure 1). An adaptive volumetric mesh of approximately 0.5 M tetrahedral elements was generated in ScanIP. The FE mesh was then exported into Abaqus (V. 6.14 Simulia, Providence, RI). Boundary conditions were assigned to match the experiment (impactor velocity, 122 mm/s; time, 0.135 s; force, 2 N). A 3D sub-modeling approach was also implemented. The element size of the mesh in this second level model was ~10 times smaller than in the global model, producing a higher resolution of the stresses in the FE white and gray matter.

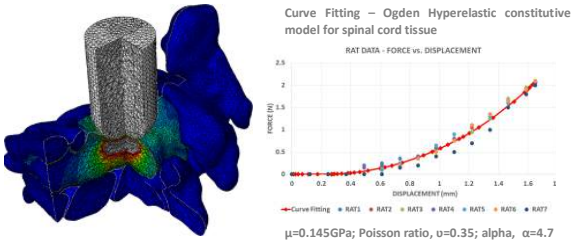

Figure 1. FE mesh, and numerical simulation of impact (Left). Results from the FE inverse model and their comparison with experimental data. Damage parameters: shear modulus, μ; Poisson ratio, υ and alpha, α (Right).

Results

Probability density and cumulative distribution function were plotted for the strain measured on the spinal cord directly under the impactor. 90%, 95% and 99% of the cumulative probability was achieved respectively at 0.163, 0.174 and 0.193 strain. With the maximum limit of 0.19, the strain map from the simulation matched the histologic results of the rat injured spinal cord with higher strain values close to the lesion area.

Discussion

The comparison of the results from the experimental animal model and the output of the FEM indicate that strain is a good predictor of tissue damage thresholds. Scaling the FEM model may be used to inform the biomechanics in larger animal models and possibly in human SCI.

References

1. Anderson, D.K. et al, Spinal Cord, 43:453-458, 2005.
2. Sharif-Alhoseini, M. et al, Spinal Cord, 55:714-721, 2017.
3. Maikos, J. et al, J Neurotrauma, 25:795-816, 2008
4. Galle, B., et al, J Biomech, 40:3029-3033, 2007.
5. Russell, C.M. et al, J Neurotrauma , 29:1574-1585, 2012.
6. Zareen, N. et al, Exp Neurol, 297: 179-189, 2017.

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