Hyper-Viscoelastic Constitutive Material Model of the Cervical Spinal Cord to Predict Impact Response

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Abstract

Background:

Cervical spinal cord injuries (SCIs) can range from minor to fatal, with high social, economic and individual impacts. Although epidemiology and experimental testing have provided important insights into SCIs, computational Human Body Models (HBMs) can provide a new perspective into the response of the human body in a variety of impact scenarios. Although the low compliance of the spinal cord likely does not affect the gross kinematics of the head and neck during an impact, the prediction of injury at the spinal cord tissue level requires a detailed representation of the tissue and the prediction of stresses and strains within the tissue. Therefore, accurate geometry, representative material properties, and injury thresholds are needed. However, prior to implementing a spinal cord within a HBM, tissue level assessment is needed.

Problem Statement:

Incorporating a spinal cord into a current HBM can enhance the ability to assess SCI risk while providing an important boundary condition for the brain and brainstem, which are currently treated with simple fixed boundary conditions in many HBMs. However, implementation requires a verified and validated material constitutive model, and numerical representation of the spinal cord and pia mater.

Objective:

The goal of the study was to identify material properties of the cervical spinal cord and pia mater that describe the mechanical response under quasi-static and dynamic impact scenarios. As a first step towards implementing a spinal cord in a HBM, these properties were implemented in a hyper-viscoelastic constitutive model and assessed using experimental impact data on the bovine spinal cord (Persson et al., 2009).

Methodology:

Spinal cord compression test data (Jannesar et al., 2018) was used to fit the Ogden hyperelastic and Prony series viscoelastic constitutive model parameters using LS-OPT. Single element test

cases at multiple strain rates were performed to verify the implementation. A finite element model of the spinal cord (solid elements) and pia mater (shell elements) was created in a commercial explicit FE code (LS-DYNA, Livermore Software) and the numerical model was assessed using impact test data for bovine spinal cord. The time and magnitude of the spinal cord – pia mater deformation were compared to the experimental results. A sensitivity study was performed to assess the dominant parameters in the response, and a mesh convergence study was undertaken.

Data to be Included:

The hyper-viscoelastic constitutive model parameters and response of the spinal cord FE model in the simulated impact tests, including a sensitivity analysis, will be presented. The modelling methodology, mesh convergence study, and comparison to experimental results will be summarized.

Results:

Identified parameters of the Ogden constitutive model with a viscoelastic Prony series accurately represented the spinal cord stress-strain data reported in the literature (Jannesar et al., 2018). The simulated impact scenario (Persson et al., 2009) and sensitivity study revealed that pia mater was a primary contributor to the maximum deformation while the spinal cord governed the initial rate of deformation. Moreover, the unloading phase of the simulated impact experiments was complex and depended on the properties of both tissues. The proposed models were assessed using the cross-correlation method and found to be in a good agreement with the experimental data.

Conclusions:

Mechanical properties of the spinal cord and pia mater were implemented in a hyper-viscoelastic constitutive model. The stiffness of the pia mater was identified as an important parameter affecting the maximum deformation of the spinal cord model when assessed using experimental impact data. The validated constitutive model and numerical implementation can now be investigated in a detailed neck model to investigate impact response and the potential for SCIs.