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

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ABSTRACT

Cervical spinal cord injuries (SCIs) can range from minor to fatal, with large social, economic and individual impacts. Although epidemiological studies and experimental testing have provided important insights into SCIs, computational Human Body Models (HBM) can provide new perspectives into the response of the human body in a variety of impact scenarios. In this study, material properties of the spinal cord were implemented in a hyper-viscoelastic constitutive model and evaluated with single element cases. A spinal cord model including pia mater was then created and assessed using transverse impact experimental data. The model prediction, based upon independently measured material properties, was in good agreement for the loading phase and maximum deformation.

INTRODUCTION

Cervical spinal cord injuries (SCIs) are devastating and life-threatening injuries with tremendous individual and societal impacts. The prevalence of SCIs is reported to be 906 per million individuals in the United States (Fehlings et al. 2014), with an estimated lifetime cost ranging between \$1.5 to \$3 million (Krueger et al. 2013). Almost 40% of SCIs since 2015 are associated with vehicle impact scenarios (NSCISC Annual Report, 2018). These injuries are associated with significant anatomical and clinical sequela that make developing a deeper biomechanical understanding challenging through epidemiological or experimental investigations alone. Computational Human Body Models (HBM) can potentially add new insights into the nature of SCIs, allowing for quantitative evaluation of tissue level biomechanics under various impact scenarios. However, HBM simulations are highly dependent on anatomically correct geometries, representative material models and accurate boundary conditions to precisely predict tissue level injury risk in highly compliant soft tissues like the spinal cord. Therefore, a first step towards implementing cervical spinal cord tissues in HBM is validation of the material properties at the tissue level.

A review of spinal cord mechanical properties in the existing literature identified the importance of viscoelasticity (Fiford and Bilston 2005; Sparrey and Keaveny 2011; Jannesar et al. 2018) and hyperelasticity (Ichihara et al. 2001) in the tissue behaviour. With regards to implementing these material properties computationally, many of the existing finite element (FE) studies of the spinal cord have used either simplified elastic (Wilcox et al. 2004; Li and Dai 2009) or hyper-elastic (Persson, Summers, and Hall 2011; Khuyagbaatar, Kim, and Hyuk Kim 2014) material models. Other investigations (Bilston 1998; Maikos et al. 2008) have tried to implement hyper-viscoelastic models to represent the mechanical properties of the spinal cord. One study (Jannesar, Nadler, and Sparrey 2016) proposed user-defined material properties based on a hyper-viscoelastic matrix with reinforced fibres in rostrocaudal direction. However, each of these models are either assessed against quasi-static validation cases or used simplified mechanical properties of the spinal cord.

OBJECTIVE

The goal of this 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).

METHODS

Spinal Cord Constitutive Model

Spinal cord compression test data (Jannesar et al., 2018) was used to fit the Ogden hyperelastic (Ogden 1972) and Prony series viscoelastic constitutive model parameters using LS-OPT (LSTC, Livermore, US). Viscoelastic effects were considered using a convoluted integral of Prony series relaxation functions. In the case of uniaxial stress, the Ogden strain energy density function (Equation 1) represents stresses in the material, where the first term is the hyperelastic component while the second term represents the viscoelastic component of stress.

$$\sigma_1 = \sum_{i=1}^{n} \mu_i \left(\lambda_1^{\alpha_i} - \lambda_1^{-\frac{1}{2}\alpha_i} \right) \quad + \quad \int_0^t g(t - \tau) \ \frac{d\varepsilon}{d\tau} d\tau \ \ (Equation\ 1)$$

$$g(t) = \sum_{j=1}^{m} G_j \, e^{-\beta_j t} \ (Equation\ 2)$$

The hyperelastic response coefficients (α_i, μ_i) were fitted using a least squares method to experimental compression data (Jannesar et al. 2018) on non-human primate (Macaca mulatta) cervical spinal cord at a strain rate of 0.32 s^{-1}.

The viscoelastic Prony series coefficients (β_j and G_j) (Equation 2), were identified using a stepwise optimization approach with experimental data at three additional strain rates. The initial values of the first pair β_1 and G_1 were estimated from the experimental data. Optimization of the coefficients was then undertaken using LS-OPT software using single element simulations with a least square fit algorithm. The first pair of β_1 and G_1 were then fixed and the higher strain rate curve (25.5 s^{-1}) added to the optimization stage. This resulted in a second pair of viscoelastic Prony coefficients being added to the model to provide a response to this higher strain rate. The process was repeated for the highest stress-stretch curve (77.5 s^{-1}). Finally, incorporating all the identified parameters, all parameters were optimized simultaneously.

Mechanical Properties of Pia Mater

For the implementation of pia mater, the experimental results from Kimpara et al. 2006 and Ozawa et al. 2004 were used. Reviewed mechanical properties were implemented in a linear elastic orthotopic constitutive model with a longitudinal elastic modulus of 25.4 MPa and 2.3 MPa in the circumferential direction.

Validation Case

A dynamic impact experiment on the bovine spinal cord-pia mater complex (Persson 2009; Persson et al. 2009) was used as a validation case. In this study, bovine spinal cord-pia mater specimens of 140 mm in length were clamped and pre-strained to 8% engineering strain. The spinal cord-pia mater complex was impacted with pellets (7g) with a velocity of 4.5 m/s; thus, in each impact kinetic energy was constant (~ 0.07 J). Each impact event was recorded with a high-speed video camera and the deformation of the spinal cord versus time was plotted. All time deformation histories were digitized and the average curve was obtained using methodology from Mattucci and Cronin, 2015.

Finite Element Model of Impact Test

A FE model of the impact test (Figure 1) was developed using the reported geometry from the experimental tests. The FE model comprised the spinal cord (hexahedral elements), pia mater (shell elements) and the pellet (hexahedral elements) was created in a commercial meshing software (HyperMesh, Altair Engineering, Troy, US). The nominal element size was 0.8 mm, while mesh sizes of 0.57 mm and 1.12 mm were used for the mesh refinement study. The ratio between adjacent mesh sizes equals 1.4.

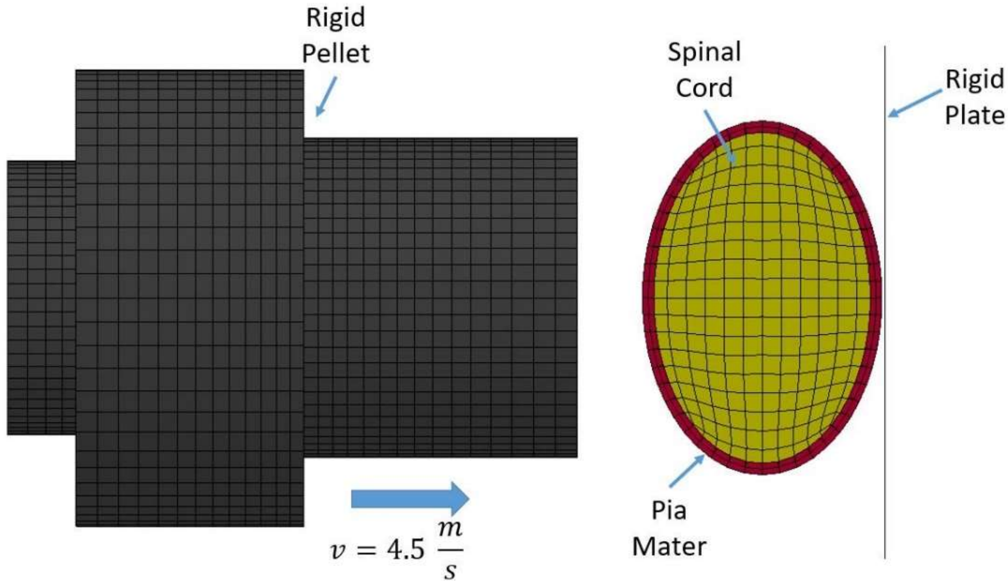

Figure 1. Simulated set up of the dynamic impact on the bovine spinal cord.

RESULTS

A two-term Ogden model (Table 1) provided an excellent fit (R^2= 0.99) to quasi-static stress-strain curve (0.32 s^{-1}). The viscoelastic material properties were assessed using single element models (Figure 2) and found to accurately represent the spinal cord stress-strain data with a cumulative $R^2 = 0.95$ (Table 2)

Table 1: Fitted hyperelastic Ogden model coefficients	
$\mu_1 = 2.96$	$\alpha_1 = -1.53$
$\mu_2 = -2.65$	$\alpha_2 = -2.24$

Table 2: Fitted viscoelastic Prony series coefficients	
$G_1 = 3\ kPa$	$\beta_1 = 0.017\ s^{-1}$
$G_2 = 1.12\ kPa$	$\beta_2 = 0.12\ s^{-1}$
$G_3 = 1.94\ kPa$	$\beta_3 = 0.58\ s^{-1}$

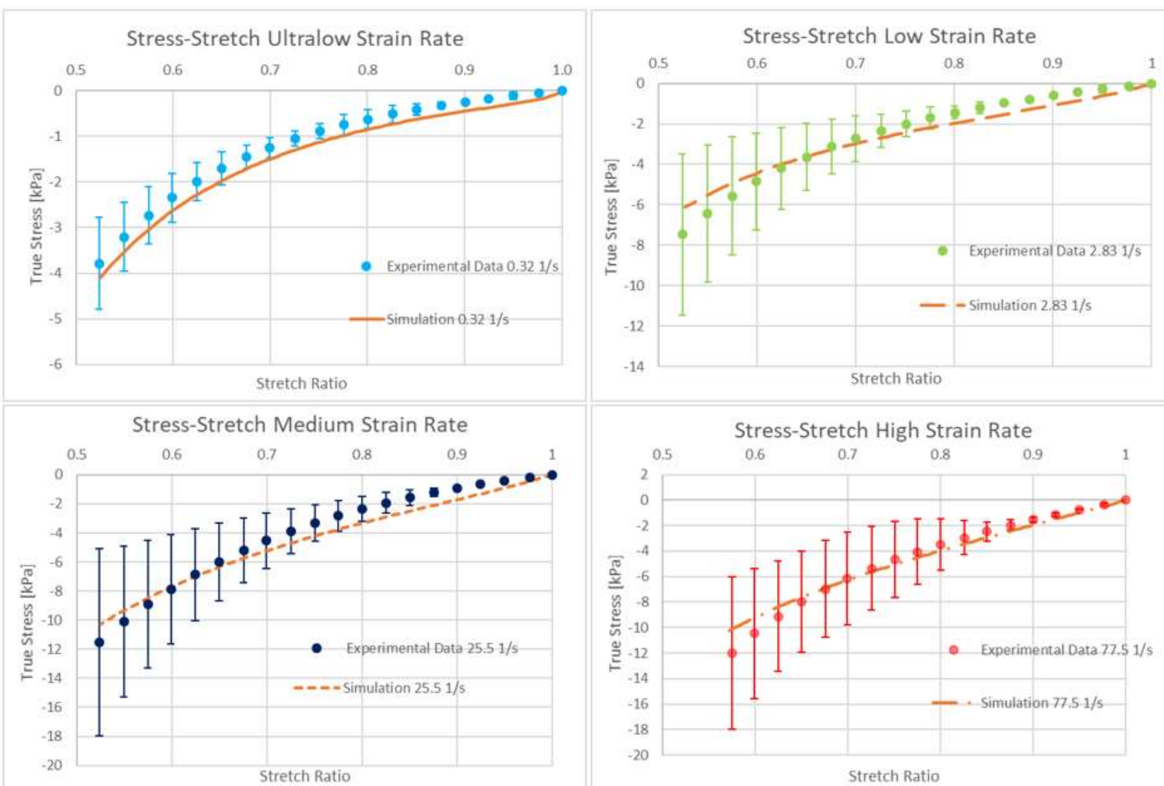

Figure 2. Single element verification of fitted hyper-viscoelastic Ogden model at a given strain rate.

The pellet impact simulation was compared to the reported deformation versus time data (Figure 3) and generally fell within the variability of the experimental data. The maximum deformation results for all three pellet impacts (Table 3) with differences in maximum displacement ranging from 1.3 to 16.4%.

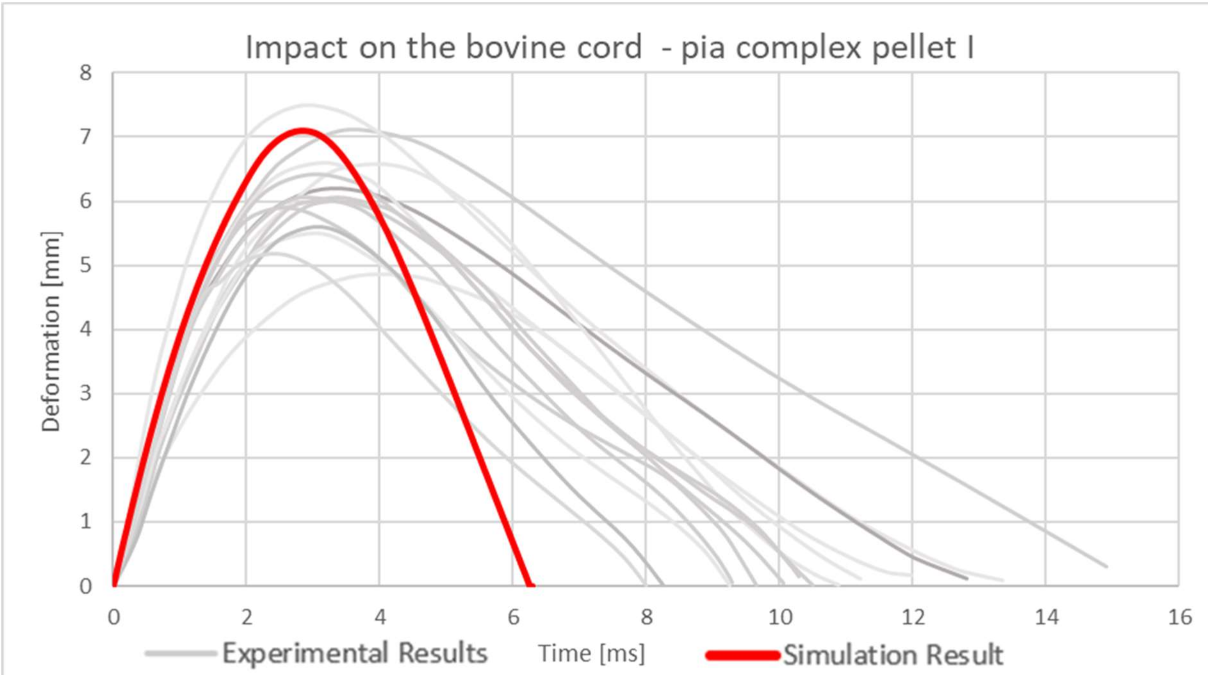

Figure 3. Time deformation histories of the simulation and exemplary experimental result for Pellet 1.

Table 3: Maximum deformation of the spinal cord-pia complex (in millimetres)			
	Pellet I	Pellet II	Pellet III
Simulation result	7.09	7.80	8.65
Averaged experimental result	6.09	6.93	8.76
Difference	16.4 %	12.5%	1.3%

DISCUSSION AND CONCLUSIONS

Dynamic impact simulations of the spinal cord and pia mater demonstrated that the model was in general agreement with the experiments with respect to the loading and maximum deformation. However, the unloading phase of the impact was not predicted accurately by the model. This may be explained, in part, by investigating the predicted response of the model. The impact simulation revealed that strains present in the spinal cord exceed the range of strains reported in the compressive experimental data used to fit the Ogden model. With respect to strain rate, the experimental data included a maximum compressive strain rate of 77.5 s^{-1}. In the simulated impact test, strain rates as high as 500 s^{-1} were identified and suggest a need for higher deformation rate data of the spinal cord.

Finally, the numerical representation of the pia mater did not account for viscoelastic effects, owing to the limited data available in the literature for this tissue. However, in the current model, this tissue was found to have a strong effect on the model response, in particular on the unloading response.

The current study proposed a method to fit experimental compressive data to the hyper-viscoelastic Ogden constitutive model including deformation rate effects. The fitted model accurately represented the spinal cord in the range of strain rates tested in the compressive experiment. The model predicted the loading phase and the maximum deformation of the spinal cord-pia mater complex in the impact simulation for all three pellets. 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.

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