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Finite Element Modelling Of an Anatomically Accurate Human Spinal Cord

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***Abstract* -** The spinal cord is a critical component of the human body that is responsible for transmitting motor and sensory impulses. However, the effects of mechanical loading on the spinal cord under tension and compression are not yet fully understood. Injuries or damages to the spinal cord can result in issues ranging from mild loss of motor capabilities to severe disabilities. Additionally, the complex nature of the biological tissue and its varying responses to external impact leads to difficulty in prognosis of the condition and subsequently determining the appropriate treatment. In this study, we have developed a properly scaled, 3-Dimensional CAD model of a healthy human spinal cord that is anatomically accurate, based on microscopic images from the spinal cord atlas. We used experimental data published in the literature to define the material parameters of the tissue. The model was then validated against the experimental results found in the literature. The simulation results and the mechanical responses obtained were found to have satisfactory agreements with the experimental data. We believe our model could be used for complex cases of spinal cord injuries.

***Keywords*:** Spinal cord, Viscoelastic, Uniaxial-loading, Finite element modelling.

1. Introduction

The mechanical properties of the spinal cord are crucial for comprehending spinal cord injury mechanisms and thresholds, developing realistic spinal cord models, and tissue engineering. The literature on this topic is extensive, ranging from the famous weight drop test by Allen [1] to the studies conducted by Fiford et al. [2], all of which document the material properties and viscoelastic behaviours of spinal cord tissue.

However, there is still a significant amount of uncertainty involved in understanding the mechanical response of the spinal tissue in cases like tethered cord syndrome and other conditions where the tissue is subjected to severe stretching. Existing models and experiments do not provide accurate details about the pathologies and the affected areas because the current Finite element models of the spinal cord make use of bi-planar radiographic reconstruction technique, dual kriging or magnetic resonance imaging (MRI) which are all based on approximation from 2-D images. Such models have a major drawback of losing a lot of valuable geometrical data like the cross-sectional area, its shape and the section length because the model geometry is constructed based on crude approximation from 2-D images. So, it is necessary to have a superior model which has all the relevant details of geometry that can serve as the base model for further studies.

The present study aims to build a general 3-D model that can imitate the real specimen and serve as a platform for the study of different conditions and injuries of the spinal cord. The strains encountered by spinal cord tissue during non-pathological activity, during normal physiological movement and spinal disorders with gradual progression (like tethered cord syndrome, disk prolapse or spinal tumours) will be the focus of our research for which we are building the present model.

2. Methods

2.1. Model construction

The section contours from the microscopic images taken from Atlas [3] were refined and redrawn as a collection of points by processing it through MATLAB. The section contours captured all the salient geometrical features and was a good approximation of the original image in both the transverse and longitudinal directions. The CAD model built based on the new contours retained most of the original geometry and its shape, while smoothening the sharp edges to avoid singularities while meshing. This model is a very close imitation of the real biological tissue and consists of all the 31 sections of the spinal cord with accurate measurements. The CAD model was then meshed with Tetrahedral (C3D4) elements and the optimal mesh size was determined based on the mesh convergence study conducted. For all the simulations a model consisting of ~1 million elements and ~5 million nodes were chosen.

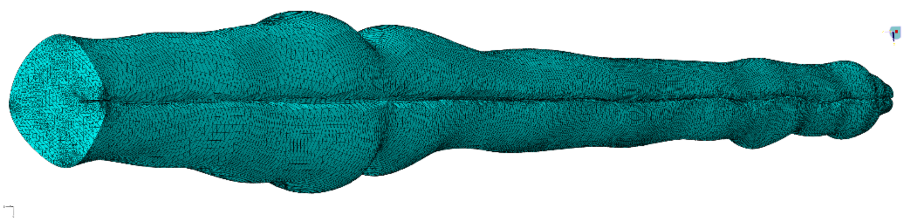

Fig. 1: Meshed profile of the full Spinal cord CAD model.

2.2. Material Modelling

In this study, we adopt the material model developed by Fiford et al. [2] based on the concept of Quasi Linear Viscoelastic (QLV) theory, which advocates for a clear separation of stress-relaxation function into time-dependent and elastic portions. The material function $Y(\varepsilon, t)$ proposed is as follows,

$$Y(\varepsilon, t) = \sigma(\varepsilon) \cdot G(\varepsilon; t) \quad (1)$$

where, $\sigma\ (\varepsilon,\ t)$ is the elastic response and $G\ (\varepsilon\ ;\ t)$ is the relaxation function, they adopted a Prony series representation for the relaxation modulus $G\ (\varepsilon\ ;\ t)$ in their study. A Prony series representation consists of a model with a few Maxwell elements in series and a spring in parallel with the whole setup. The relaxation modulus for this material has the form below [4], The sum of the exponential is known as the Prony series.

$$G(t) = G_\infty + \sum_{i=1}^{N} G_i^{-\nu_i t} \quad (2)$$

where G_∞ is the steady-state stiffness (represented by the parallel spring), and G_i and ν_i with $i = 1 \ldots N$ are the time constants and stiffnesses of the Maxwell elements. These parameters are used directly as the properties of the material and the values mentioned in the below table taken from Fiford et al. [2].

Table 2: Material Properties.

Density (kg/ m^3)	Poisson's ratio	G_∞	G1	ν1	G2	ν2
1049	0.45	320KPa	0.0190	1.4079	0.8092	46.4037

2.3. Model Validation

To validate our Spine model, we replicated the experiment conducted by Bilston et al. [5] on the cervical spinal cord samples obtained from human cadavers. The simulation results for stress-strain response are compared against the experimental data published in their paper. The results of the validation study are discussed in the subsequent section. The material properties of rat spine are used for the study, this is because a comprehensive study undertaken by Jaumard et al. [6], suggests that the similar spinal morphology in the axial plane between rats and humans supports the validity of using the rat spine to study the effects of axial and shear loading on the human spine. Mesh convergence study was done to determine the optimum mesh size and simulations were run with the same. Boundary conditions were applied to represent a uniaxial tension condition:

- Cervical end: Rotation and Translation are fixed (Encastre)
- Sacral end: A displacement boundary condition with strain rate $0.2S^{-1}$ is applied.

3.Results and Discussion

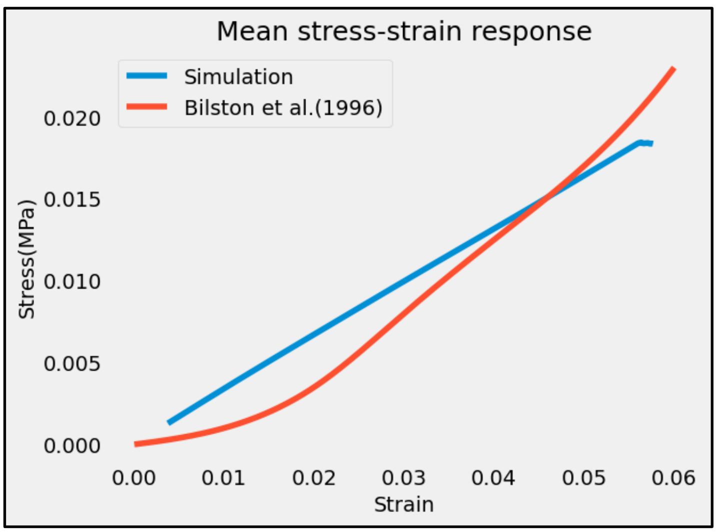

Fig.2: Comparison of Mean stress-strain response of the simulation and experimental results.

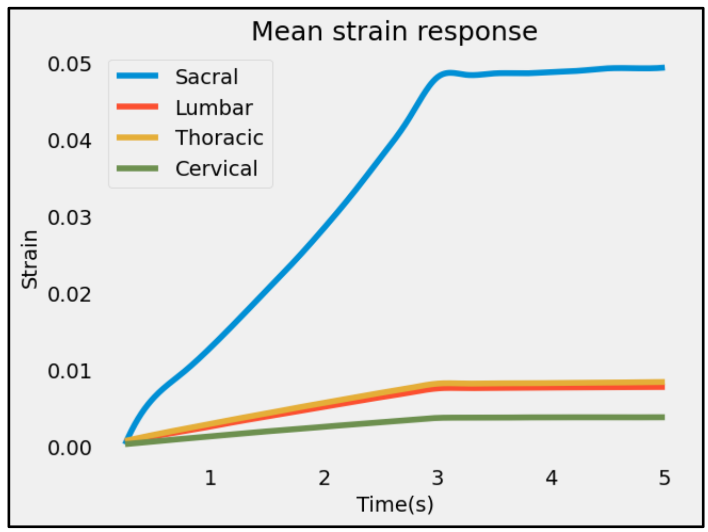

Fig.3: Simulation results of mean strain variation with time in different sections of the spinal cord.

The model validation results represented in Fig.2 demonstrate that the stress-strain curve closely matches the behaviour of the actual specimen. However, in case of the simulation the stiffness modulus is uniform and monotonously increasing whereas the response from real tissue appears to be compliant initially and becomes stiffer as the load increases. This behaviour is expected because, for our study, we have assumed our tissue to be a homogeneous, isotropic solid material, but real biological tissues contain fibrous materials which will be porous, have a sparse material packing and the fibres will have different orientations. This type of porous nature of the spinal cord could be the reason for the initial compliance. However, as the fibres straighten out, the tissue may become stiffer.

From Fig.3, it is apparent that the distribution of strain and subsequently the stresses are non-uniform within the specimens. The viscoelastic nature of the material is responsible for this type of non-uniform strain response, with different vertebral levels experiencing differing amounts of strain. If we consider the rostro-caudal plane, areas closer to the loading end displays the maximum strain and vice-versa. This makes the regions that are farther from the sacral end the least stressed part. Correspondingly, the cervical region has the lowest strain values and sacral regions the highest.

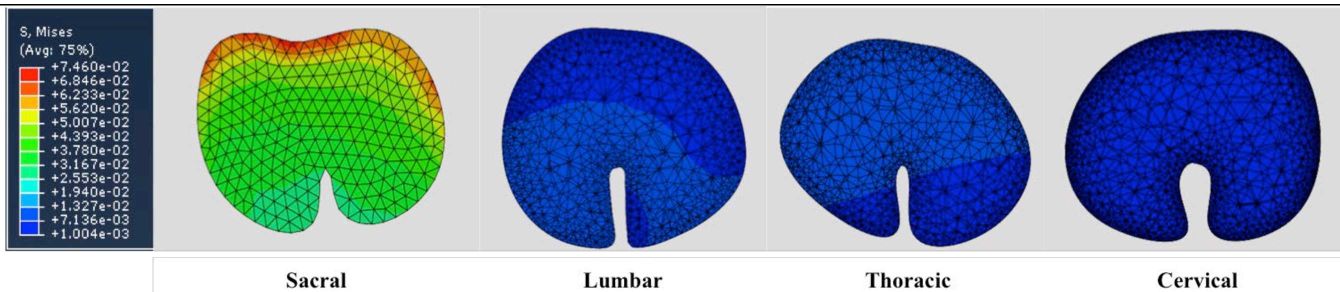

Fig. 4: Contour maps displaying the von mises stress variation across the spinal sections at different regions of the Cord.

The contour maps provide a visual representation of how the stress distribution varies across different sections of the spinal cord. They also illustrate how the maximum stress value and its position change with variations in the cord's geometry along its length. The stress distribution map is taken in the sagittal plane direction. The figures correspond to Von Mises stress variation in the sacral, lumbar, thoracic, and cervical regions, with dark blue indicating the lowest stress values and red indicating the maximum. It is noteworthy that the maximum stress values are distributed differently across various sections of the cord, with the dorsal portion of the sacral region experiencing the highest stress. This observation is intriguing because one would expect the stress value at the groove to be maximum. This finding clearly indicates that the geometry (shape and thickness) of the cord has a greater influence on the stress distribution than any other factor.

4. Conclusion

This study emphasizes that the material properties of the rat spine can be utilized to model the human spinal cord successfully. The simulation results obtained from the model are in reasonable agreement with the experimental data published in the literature. The spinal cord's stress-strain response to uniaxial loading conditions highlights the importance of the cord's geometry in mapping the high-stress regions. Similarly, the simulation response reveals presence of high stress zones in the dorsal part of the sacral region when the cord is subjected to stretching conditions. We believe that the present model can be extended to study spinal cord deformations for complex injury cases.

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