Assessment of Spinal Cord Tissue Deformation During Central Compression and Fracture in a Functional Spinal Unit Finite Element Model

Aleksander Rycman, Sophia Ngan, Jarrod Carter, Duane S. Cronin

I. INTRODUCTION

Spinal cord injuries (SCIs) may result from damage and intrusion of surrounding tissues, such as vertebral fracture, leading to compression of the spinal cord [1]. Functional Spinal Unit (FSU) axial compression experiments to fracture reported the resulting spinal canal occlusion and highlighted the importance of investigating the occlusion of the spinal canal at the time of injury [2]. A recent advance in modeling the post-fracture response of vertebrae, and subsequent occlusion of the spinal canal, was presented in an enhanced FE FSU (C5-C6-C7) model that was extracted from the GHBMC 50th percentile male model (M50). The enhanced FSU model utilised Smoothed Particle Hydrodynamics (SPH) to represent damaged trabecular bone fragments, enabling modeling of intrusion into the spinal canal [3]. Additionally, a validated and anatomically verified representation of cervical spinal cord tissue with cervical nerve roots was implemented in the GHBMC M50 model [4]. The current study aimed to integrate the SPH for post-fracture prediction with the spinal cord tissue in a FSU to assess the spinal cord and nerve root deformation within the tissue during central compression.

II. METHODS

The previously developed FE FSU model that was used to investigate central compression [5], hard tissue post-fracture behaviour and occlusion [3] was integrated with the spinal cord [4], pia mater, dura mater and cerebrospinal fluid (Fig. 1 A)–B)) (FSU_{SC}). The model was subjected to experimental boundary conditions, including an initial 40 N pre-load that was followed by a vertical displacement boundary condition up to 15.3 mm. Boundary conditions were applied to the top potting of the C5 vertebra (Fig. 1A)). The bottom potting was fully constrained, fixing the motion of the C7 vertebra. The FSU_{SC} model was solved in a commercial explicit FE hydrodynamic code (LS-DYNA R13, LST, Livermore, CA). The deformations in the spinal cord and nerve roots were assessed by plotting the anterior-posterior length of the spinal cord at the location of largest occlusion, and the diameter of the nerve roots in the extraforaminal space.

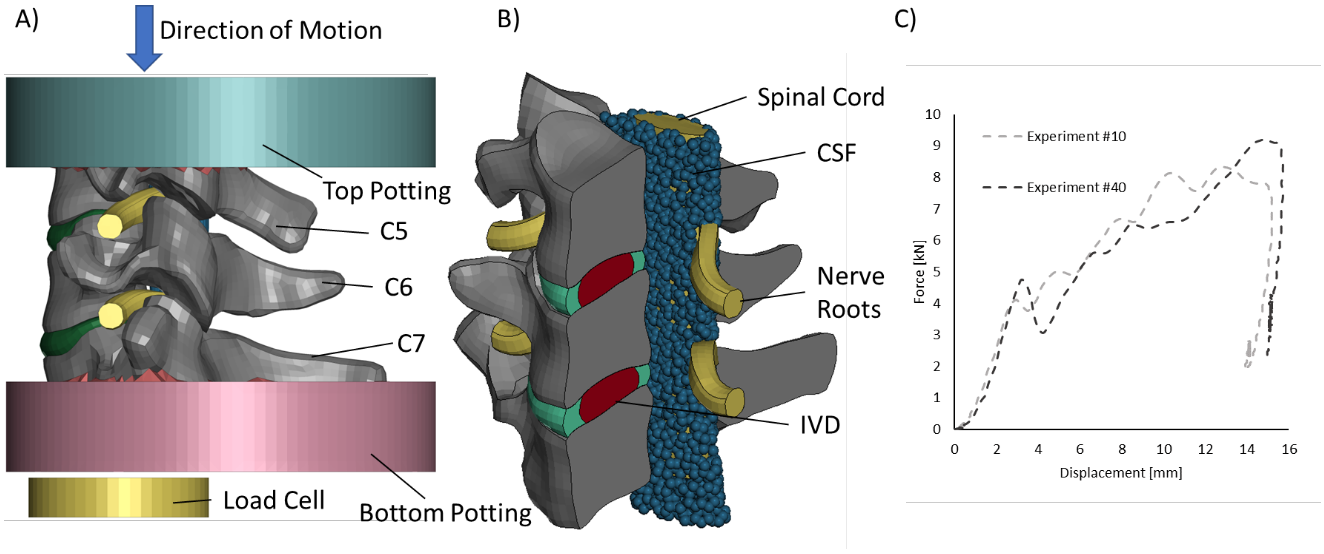

Fig. 1. A) Side view of the FSU_{SC} model showing the re-created experimental setup and the direction of motion; B) the cross-sectional view detailing implemented nervous tissues inside the spinal canal; C) the experimental force-displacement traces [2].

III. INITIAL FINDINGS

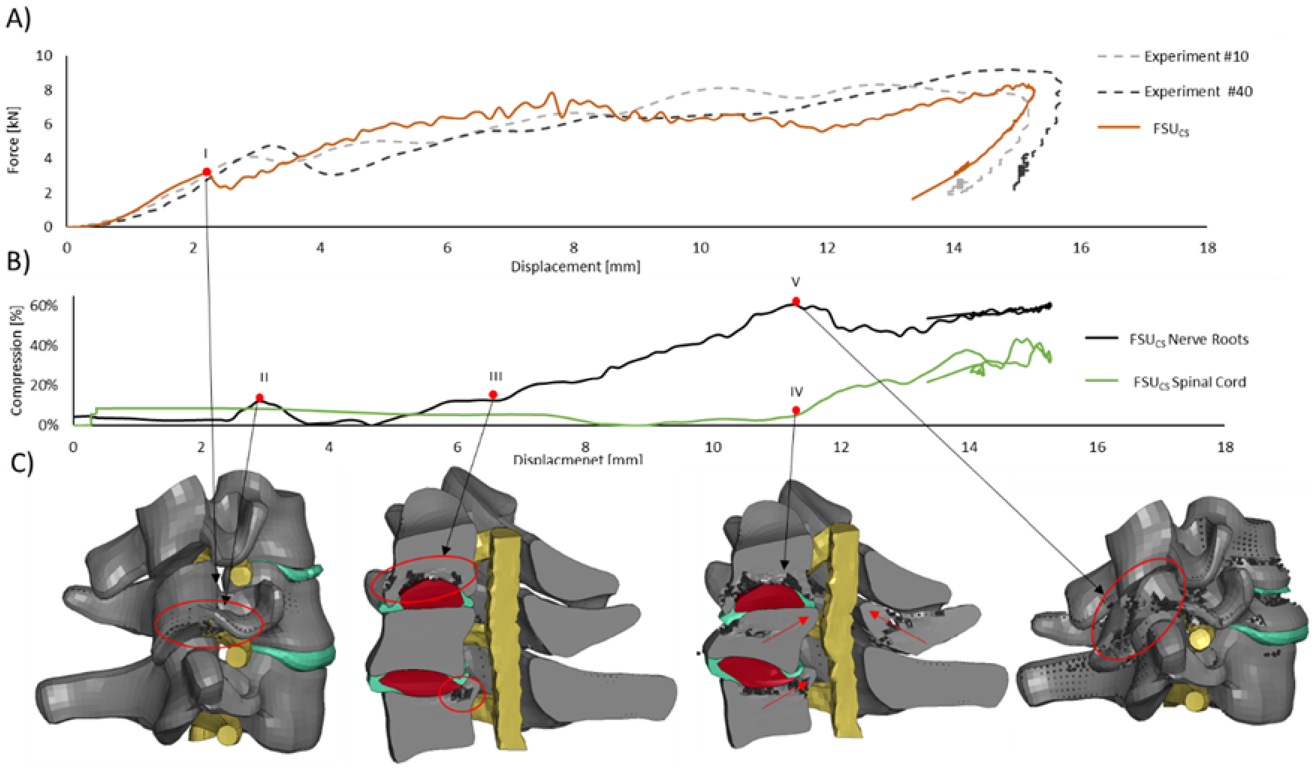

Fig. 2. A) Comparison of the force-displacement traces of the FSU$_{SC}$ and experimental data [2]; B) compression of the spinal cord (anterior-posterior) and the C6 nerve root during simulation of the FSU$_{SC}$ model; C) visualisation of crucial moments throughout axial compression of the FSU$_{SC}$ model.

The force-displacement response of the FSU$_{sc}$ model agreed with experimental data [2], reaching 8.4 kN at 15.1 mm of displacement. The compression responses of all four nerve roots were similar; therefore, the analysis presented here was conducted for the left C6 nerve root. The initialisation of fracture of the C6 pedicle (I) caused an initial reduction of the nerve root diameter of around 10% (II). As the force increased, fracture initiated in the C5 and C7 vertebral bodies (III); eroded bony parts (SPH elements) continued to provide structural support to the FSU$_{SC}$ model. The fracture in the pedicle progressed, causing further compression to the C6 nerve root. The progression of the fracture in the vertebral bodies (C5-C6-C7) and the C6 posterior spinous process caused relative rotation of the vertebral bodies and intrusion in the spinal canal (IV). At this stage, the eroded bony parts intruded into the spinal canal causing a non-uniform deformation of the spinal cord. The catastrophic fracture of the articular process compressed the nerve roots by up to 60% (V). The spinal cord continued to deform up to 44% as more material flowed into the spinal canal.

IV. DISCUSSION

The nerve roots were compressed as fracture initiated and progressed in the pedicle. Initial assessment revealed that the spinal cord was compressed when the fracture in the vertebral body and the catastrophic fracture in the articular process occurred. The general fracture pattern of the FSU$_{SC}$ agreed with experimentally reported vertebral body fracture, intrusion of the intervertebral disc into the vertebral bodies and fracture of the articular pillars. Compression of the spinal cord and nerve roots in the FSU$_{sc}$ model were on the order of 50% and the highest occlusion occurred at the C6 level. The experimental study [2] did not include the nervous tissues and therefore did not report the cervical level of the highest occlusion. Literature data [6] indicate that a ~40% compression of the spinal cord tissue corresponds to severe injury and neurological sequela. The proposed modeling method provides a platform for assessing SCI and can be extended to full HBM.

V. References

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