North American Spine Society Journal (NASSJ) 15 (2023) 100246

Contents lists available at ScienceDirect

North American Spine Society Journal (NASSJ)

journal homepage: www.elsevier.com/locate/xnsj

Systematic Reviews /Meta-analyses

# Finite element modeling of the human cervical spinal cord and its applications: A systematic review

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ARTICLE INFO

*Keywords:*
Finite element modeling
Biomechanics
Cervical spinal cord
Spinal cord injury
Trauma
Spine surgery
Ossification of the posterior longitudinal ligament
Ligamentum flavum hypertrophy

ABSTRACT

*Background Context:* Finite element modeling (FEM) is an established tool to analyze the biomechanics of complex systems. Advances in computational techniques have led to the increasing use of spinal cord FEMs to study cervical spinal cord pathology. There is considerable variability in the creation of cervical spinal cord FEMs and to date there has been no systematic review of the technique. The aim of this study was to review the uses, techniques, limitations, and applications of FEMs of the human cervical spinal cord.

*Methods:* A literature search was performed through PubMed and Scopus using the words finite element analysis, spinal cord, and biomechanics. Studies were selected based on the following inclusion criteria: (1) use of human spinal cord modeling at the cervical level; (2) model the cervical spinal cord with or without the osteoligamentous spine; and (3) the study should describe an application of the spinal cord FEM.

*Results:* Our search resulted in 369 total publications, 49 underwent reviews of the abstract and full text, and 23 were included in the study. Spinal cord FEMs are used to study spinal cord injury and trauma, pathologic processes, and spine surgery. Considerable variation exists in the derivation of spinal cord geometries, mathematical models, and material properties. Less than 50% of the FEMs incorporate the dura mater, cerebrospinal fluid, nerve roots, and denticulate ligaments. Von Mises stress, and strain of the spinal cord are the most common outputs studied. FEM offers the opportunity for dynamic simulation, but this has been used in only four studies.

*Conclusions:* Spinal cord FEM provides unique insight into the stress and strain of the cervical spinal cord in various pathological conditions and allows for the simulation of surgical procedures. Standardization of modeling parameters, anatomical structures and inclusion of patient-specific data are necessary to improve the clinical translation.

## Introduction

Finite element modeling (FEM) is an established technique to understand the biomechanics of complex systems including human neuroanatomy. Finite element modeling breaks down complex anatomical geometries into small elements with specific material properties, which allows computational analyses to be conducted with simulated loads. Biomechanical testing using FEM overcomes the limitations of cadaver models and can be used to measure intrinsic tissue forces where clinical testing is not feasible [1–4]. Traditional biomechanical testing of the spine requires testing of cadaver preparations of the spine often without the paraspinal muscles. Specifically, the spinal cord cannot be tested in cadaver models since spinal cord tissue properties are not maintained during cadaver preparation and intrinsic stress cannot be measured. Limitations of cadaver models that are overcome by FEM include biological variability, difficulty with procurement, sophisticated testing capabilities, and costs. While a single cadaver can only simulate a single surgical intervention, FEMs can simulate and compare multiple surgical interventions in a single model because of its absolute repeatability and ability to explore the responses for the specific anatomical-geometrical characteristics of each patient using patient imaging such as computed tomography (CT) or magnetic resonance imaging (MRI).

FDA device/drug status: Not applicable.

Author disclosures: ***IS:*** Nothing to disclose. ***BH:*** Grant: AO Spine North America (C). ***AW:*** Grant: AO Spine North America (C). ***YP:*** Grant: AO Spine North America (C). ***MDB:*** Grants: NIH, DOD, VA (F). ***NY:*** Grant: AO Spine (C). ***AV:*** Grant: AO Spine North America (C); Advancing a Healthier Wisconsin (F, Paid directly to institution/employer).

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https://doi.org/10.1016/j.xnsj.2023.100246
Received 31 May 2023; Received in revised form 1 July 2023; Accepted 23 July 2023
Available online 27 July 2023

Finite element modeling's of the vertebral column is used extensively to study biomechanical responses of the human spine to loading, injury, and surgical intervention. Advancement in computational modeling as well as knowledge of the material properties of neural tissues has led to the development of FEMs of the spinal cord. The development of a spinal cord FEM requires several inputs, which contribute to the accuracy and validity of the model. To begin with, accurate MRI-derived spinal cord geometries need to be obtained. Cervical spine and spinal cord geometries need to be recorded from medical imaging data such as MRI or CT scans. The segmented components must be discretized with optimal element formulation and an appropriate number of elements. In addition, the material properties of the bone, ligament, and soft tissues are modeled with different constituents of materials, which are obtained from experimental studies. Furthermore, boundary conditions, constraints, and contacts are established between components to reflect realistic physiological conditions and interactions. Finally, the external forces and moments applied to the FE model must be determined to simulate the physiological conditions being studied. This technique is now used to study spinal cord stress and strain states due to spinal cord pathology and traumatic injuries. Finite element modeling's of the human spinal cord enable quantification of spinal cord forces in dynamic environments as well as after simulated surgical interventions.

The application of FEM to spinal cord biomechanics research started around the 1980s. At first, these models were predominantly 2D due to computational limitations. During this time, FEMs provided valuable insights into the behavior of the spinal cord under various physiological conditions. Coburn et al. [5] used a 2D model to understand the effect of epidural electrode-induced electrical stimulation on the spinal cord. In the early 2000s, advancements in computational capacities allowed for a shift toward 3D FEMs. These 3D models provided a more accurate representation of the anatomical and biomechanical complexities of the spinal cord [6]. Over the past decade, FEMs have been employed to study more complex and diverse clinical scenarios. This includes analyzing the stress in the spinal cord due to degenerative cervical myelopathy [7], understanding the impact of cerebrospinal fluid representation during transverse impacts [8], and investigating the effects of contusion load on the cervical spinal cord [9]. Some studies also explored the biomechanics of surgical interventions [10] and surgical treatment for cervical myelopathy [11]. Recently, more sophisticated modeling techniques have been developed, such as hyper-viscoelastic multiphysics finite element models [12], and patient-specific finite element models [13] for the cervical spinal cord. These advancements have expanded our understanding of cervical spinal cord biomechanics and hold promise for guiding surgical strategies, understanding spinal cord pathobiology and driving innovations in the field. There is considerable variability in methodology as well as applications of cervical spinal cord FEMs and to date there has been no review summarizing the current status, capabilities and limitations of human cervical spinal cord FEMs.

In this review of human cervical spinal cord FEMs, we address model development, material properties, testing environment, and clinical applications. We aim to define the current state, areas of need, and future directions of human spinal cord FEM for clinical applications.

## Methods

A systematic review was performed through PubMed and Scopus according to the PRISMA 2020 guidelines. The following terms were searched: (1) Finite element analysis, and (2) spinal cord, and (3) biomechanics. The results were initially screened by their titles. The abstracts were then reviewed followed by a review of the full article. Studies were evaluated for the following inclusion criteria: (1) Human spinal cord modeling at the cervical level; (2) the study should model the spinal cord with or without the osteoligamentous spine; and (3) the study should describe an application of the spinal cord FEM. Review articles, articles not in English, studies that only modeled the osteoligamentous spine, studies that focused on thoracic and lumbar regions of the spinal cord, and studies on animal spinal cord FEMs were excluded from this study.

Selected studies were evaluated for the disease process that was studied, model development, material properties used, outputs, and limitations of the models.

## Results

The search yielded 369 total results. After screening titles and removing duplicates, 49 results remained. Twenty-six more studies that did not satisfy the inclusion criteria were removed after reading through abstracts or full texts (Fig. 1). Seven studies were removed because these did not model the spinal cord [14–20], 5 studies were removed since they modeled nonhuman spinal cords [21–25], 3 studies did not use finite element analysis [26–28], and 2 studies were not in English [29,30]. Seven studies were removed because they focused on the thoracic or lumbar spinal cord [31–37]. One study was removed because it modeled the head-neck complex without a focus on the spinal cord [38]. One study was removed because it described the creation of a validated model but did not evaluate spinal pathology [39].

### *Disease process*

Nine studies (39%) looked at spinal cord injury and trauma [9,40–47]. Ten studies (43%) looked at the effect of pathologic processes (degenerative disease or trauma) on spinal cord biomechanics [7,48–56]. Four studies (17%) looked at stress and strain on the spinal cord after spine surgery [10,57–59].

### *Derivation of spinal cord geometries*

Studies had considerable variation in the methodology of FEM development for the osteoligamentous spine and spinal cord. Geometric measurements to model the neuroanatomy were obtained from neuroimaging in most studies. Eleven models (48%) were created using imaging of the human spinal cord [7,9,41,47–49,52–54,57,58]. Seven (30%) of these were CT scans [7,41,48,52–54,57] and 3 (13%) were MR imaging [9,49,56]. One study (4%) used both CT and MR imaging [47]. Six models (26%) used morphologic cross-sections from cadaveric human spinal cords [10,40,42,45,55,59]. Three models (13%) were based on institutional or published anatomical data [7,44,46]. Three models (13%) did not specify where the spinal cord geometries were derived from [43,50,51].

Nineteen studies (83%) modeled the grey and white matter of the spinal cord as separate elements with distinct material properties [7,9,40,41,43,45–51,53–59]. Four studies (17%) modeled the spinal cord as a single structure, without segmenting white and gray matter [10,42,44,52].

### *Tissue material properties*

The material properties of the spinal cord were obtained from animal or human cadaver tissue testing. Eighteen studies (78%) used bovine spinal cord tissue material properties [10,40–43,45,47–51,53–59]. One study (4%) used material properties from cat spinal cords [52]. One study (4%) used dog and cat spinal cord tissues [44]. One study (4%) used material properties from human cadaveric spinal cords [46]. Two studies (9%) did not specify how the material properties were derived [7,9].

The spinal cord was modeled according to different mathematical models. Nine studies (39%) used a nonlinear hyperplastic material model [9,10,41,52,53,56–59]. Ten studies (43%) modeled the spinal cord using linear elastic material properties [7,42,44,45,47–49,54,55]. Four studies (17%) incorporated viscoelastic material properties [40,43,50,51].

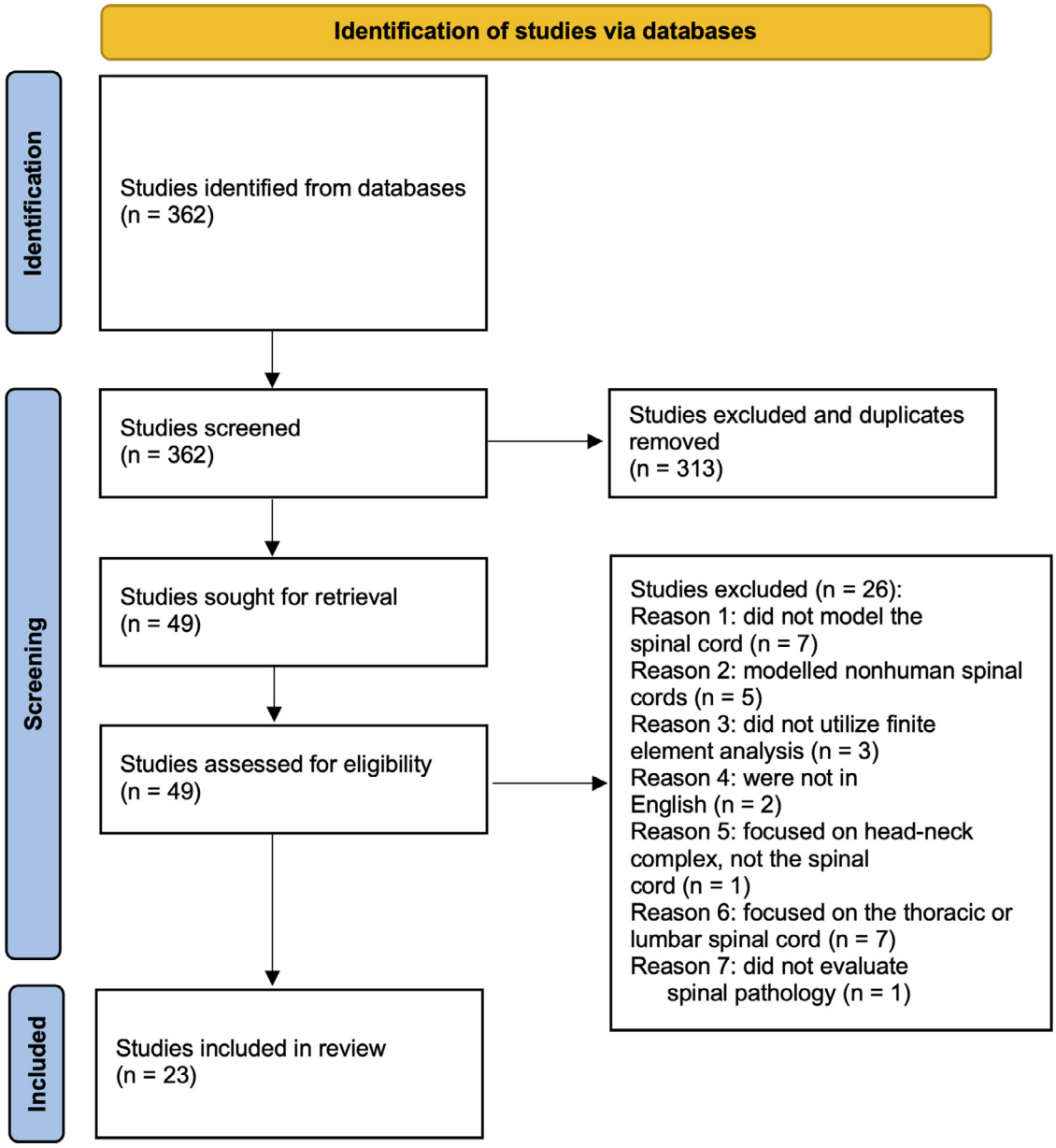


**Fig. 1.** Flow chart illustrating the literature review and selection process.

*Anatomical structures modeled*

Eleven studies (48%) incorporated dura mater [10,40,41,44,46–48,52,53,57–59] and twelve (52%) incorporated pia mater into their models of the spinal cord [9,10,40,43,47–51,54,55,57]. Denticulate ligaments were modeled around the spinal cord in ten studies (43%) [10,40,44,46–48,53,57–59]. Nerve roots were incorporated in eight models (35%) [41,46,48,52,53,57–59] Eight studies (35%) included cerebrospinal fluid [10,41,46,52,53,57–59]. CSF was modeled as a fluid element in all studies. The osteoligamentous spine also been modeled in addition to the spinal cord. These included intervertebral discs in 13 studies (57%) [7,40,43,44,46,48,50–52,55–58]. Eight studies (35%) included one or more vertebral ligaments including the ligamentum flavum or posterior longitudinal ligaments [7,40,44,46,48,49,52,53]. Bony vertebrae were included in 13 models (57%) [7,40,41,44,46–48,52,54,56–59].

*Use of patient-specific anatomy or generic anatomy of the spinal cord*

Fourteen studies (61%) developed FEM based on generic spine and spinal cord anatomy (Fig. 2) [10,40,42–46,48–51,54–56]. Nine models (39%) [7,9,41,52–54,57–59] used CT-derived patient-specific anatomy of the osteoligamentous spine, but generic geometries were used to develop the spinal cord FEM. Two studies (9%) used MRI-derived geometries from a healthy subject to construct gray and white matter elements, however, the authors stated that symmetry of the gray and white matter was assumed; so subject-specific geometries of the gray and white matter were not incorporated in the model [9,47]. No study used MRI-derived patient-specific geometries of the spinal cord (Table 1, Fig. 3).

*Vertebral segments modeled*

Twenty studies (87%) modeled the cervical spinal cord. Five of these studies (22%) modeled the entire cervical spinal cord [42,45,47,54,57].

**Table 1**
Summary of cervical spinal cord FEM studies.

| Study | Disease process | Spinal cord geometries | Tissue material properties | Type of model | Anatomical structures | Subject-specific or generic *spinal cord* anatomy | Anatomical region | Outputs |
|---|---|---|---|---|---|---|---|---|
| Yang et al. [7] | Cervical spondylotic myelopathy | CT imaging | Not specified | linear elastic | Cortical bone, cancellous bone, boney endplate, pedicle, small joints, gray matter of the spinal cord, ALL, PLL, LF, soft backbone, nucleus proposes, fiber ring, white matter of spinal cord | Generic | Cervical | von Mises stress |
| Xue et al. [57] | Effect of cervical rotatory manipulation on the biomechanics of a healthy spinal cord | CT imaging | Bovine | nonlinear hyperelastic | C1-C7 vertebral bodies, intervertebral disc, zygapophysial cartilage, nerve root complex, and vertebral contents included grey matter, white matter, pia matter, dura matter, denticulate ligaments, nerve roots, and CSF | Generic | Cervical | CSA, sagital diameter, von Mises stress |
| Levy et al. [48] | Degenerative cervical myelopathy | CT imaging | Bovine | linear elastic | Grey matter, white matter, pia mater, dura, spinal roots, dentates, IVD, vertebrae, ligaments (ALL PLL nuchal ligament LF, joint capsule, interspinous) | Generic | Cervical | Shear stress, stress, von Mises stress |
| Zhu et al. [9] | Contusion loading | MR Imaging | Not specified | nonlinear hyperelastic | grey matter white matter and pia | Subject-specific | Three segment | von Mises stress |
| Stoner et al. [10] | Cervical myelopathy | Cadaveric histologic cross sections | Bovine | nonlinear hyperelastic | grey and white matter of the spinal cord grouped together, dura, pia dentate ligaments, CSF | Generic | Cervical | Strain, von Mises stress |
| Bailly et al. [40] | Central cord syndrome | Cadaveric histologic cross sections | Bovine | viscoelastic | vertebrae, IVD, 6 spinal ligaments (ALL PLL zygapophyseal joint ligaments, LF, interspinous ligaments and nuchal ligaments), white matter, grey matter, denticulate ligaments, pia, and dura | Generic | Cervical | Strain, stress |
| Khuyagbaatar et al. [41] | Contusion, dislocation, and distraction SCI mechanisms | CT imaging | Bovine | nonlinear hyperelastic | Vertebrae, white matter, grey matter, dura mate with nerve roots, and CSF‘ | Subject-specific | Cervical | CSA, strain, stress, von Mises stress |
| Khuyagbaatar et al. [52] | Ossification of the posterior longitudinal ligament | CT imaging | Cat | nonlinear hyperelastic | Vertebrae, IVD, PLL, LF, nerve roots, grey and white matter, dura, nerve root CSF | Generic | Cervical | CSA, stress, volume, von Mises stress |
| Nishida et al. [49] | Cervical spondylotic myelopathy | MR Imaging | Bovine | linear elastic | grey matter, white matter, pia, and LF | Generic | Cervical | Stress |

(*continued on next page*)

**Table 1** (*continued*)

| Study | Disease process | Spinal cord geometries | Tissue material properties | Type of model | Anatomical structures | Subject-specific or generic *spinal cord* anatomy | Anatomical region | Outputs |
|---|---|---|---|---|---|---|---|---|
| Li et al. [42] | Acute central cord syndrome | Cadaveric Histologic cross sections | Bovine | linear elastic | spinal cord | Generic | Cervical | von Mises stress |
| Kato et al. [50] | Myelopathy due to OPLL | Not specified | Bovine | viscoelastic | grey matter white matter pia matter and IVD | Generic | Two segment | Stress |
| Kato et al. [43] | SCI in OPLL | Not specified | Bovine | viscoelastic | grey matter white matter pia matter and IVD | Generic | Two segment | Stress |
| Li et al. [45] | Hyperextension injury | Cadaver, Histologic cross sections | Bovine | linear elastic | grey matter and white matter | Generic | Cervical | Stress, von Mises stress |
| Greaves et al. [44] | Spinal cord injury | anatomic descriptions | Dog and cat | linear elastic | Vertebrae, spinal cord, dura, ALL PLL, joint capsule, LF, interspinous ligament, IVD, denticulate ligaments, and dural attachments | Generic | Cervical | Shear strain, strain, von Mises strain |
| Kato et al. [50] | Cervical flexion myelopathy | Not specified | Bovine | viscoelastic | grey matter, white matter, pia mater, and IVD | Generic | Cervical | Stress |
| Khuyagbaatar et al. [53] | Ossification of the posterior longitudinal ligament | CT Imaging | Bovine | Nonlinear hyperelastic | Dura, denticulate ligaments, CSF, nerve roots, ligaments | Generic | Cervical | Von mises stress, stress, CSA |
| Nishida et al. [54] | Brown-Séquard Syndrome | CT imaging | Bovine | Linear elastic | Pia, vertebrae | Generic | Cervical | Stress |
| Scifert et al. [46] | Spinal cord injury | Anatomic descriptions | Human | Linear elastic | Vertebrae, ligaments, IVD, nerve roots, CSF, denticulate ligaments | Generic | Cervical | von Mises stress, strain |
| Czyz et al. [47] | Spinal cord injury from burst fracture | MRI imaging | Bovine | Linear elastic | Pia, dura, denticulate ligaments, vertebrae | Subject-specific | Cervical | Deformation, stress, shear stress, strain |
| Liang et al. [55] | Herniated cervical IVD | Histologic cross sections | Bovine | linear elastic | Pia, IVD | Generic | Cervical | Stress |
| Khuyagbaatar et al. [59] | OPLL | Histologic cross sections | Bovine | nonlinear hyperelastic | Vertebrae, nerve roots, denticulate ligaments, CSF dura | Generic | Cervical | Displacement, stress, von Mises stress |
| Khuyagbaatar et al. [58] | OPLL | CT Imaging | Bovine | nonlinear hyperelastic | Vertebrae, nerve roots, denticulate ligaments, CSF, dura, IVD | Generic | Cervical | von Mises stress, strain, displacement |
| Taso et al. [56] | Cervical myelopathy | MR imaging | Bovine | nonlinear hyperelastic | Vertebrae, IVD, CSF | Generic | Cervical | von Mises stress, shear stress |

ALL, anterior longitudinal ligament; PLL, posterior longitudinal ligament; LF, ligamentum flavum; CSF, cerebrospinal fluid; IVD, intervertebral disc; SCI, spinal cord injury; OPLL, ossification of the posterior longitudinal ligament.

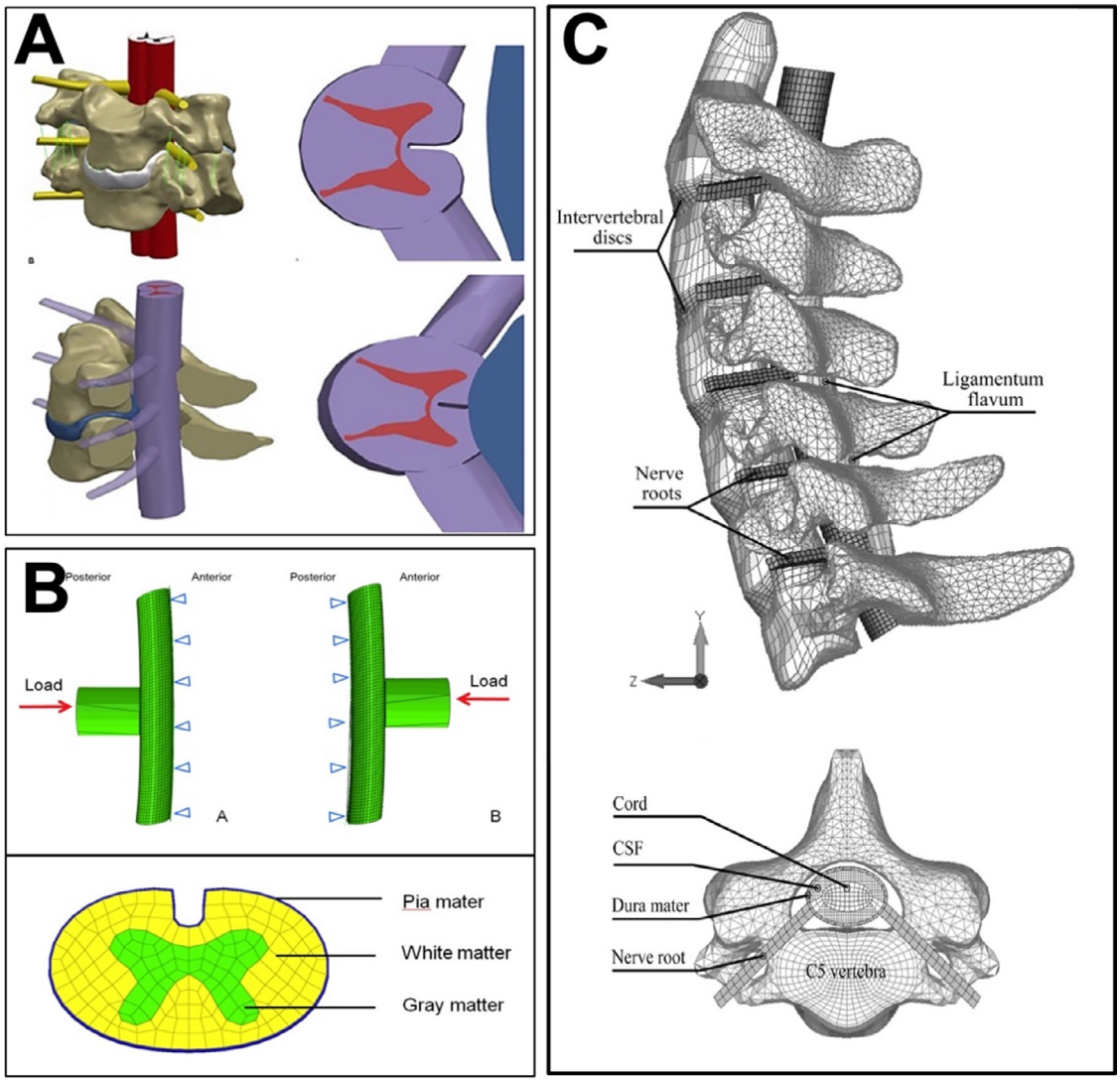


**Fig. 2.** (A) FEMs created by Yang et al [7] showing patient-specific bony anatomy but generic spinal cord anatomy and compressive pathology, (B) FEM by Zhu et al. [9] showing generic spinal cord morphology without osteoligamentous anatomy, (C) FEM by Khuyagbaatar et al. [52] showing patient-specific CT-derived bony anatomy with generic spinal cord and nerve root morphology.

Four studies (17%) included the cord from C2 to C7 [41,52,53,58]. Three studies (9%) modeled the cord from C2 to T1 [10,40,59]. One study (4%) modeled three segments of the cervical spinal cord [9]. Four studies (17%) modeled 2 segments of the cervical spinal cord [44,49,50,56]. Four studies (17%) used single-segment cervical models [7,46,48,55]. One study (4%) described a 2-segment model in an unspecified region [43].

*Outputs*

The most common FEM outputs include von Mises stress in 14 studies (61%) [7,9,10,41,42,45,46,48,52,53,56–59], stress in 14 studies (61%) [40,41,43,45,47–55,59], strain in 7 studies (30%) [10,40,41,44,46,47,58], and cross-sectional area in 4 studies (17%) [41,52,53,57]. Shear stress was measured in 3 studies (13%) [47,48,56]. Shear strain [44] and von Mises strain [44] were measured in 1 study each (4%). Displacement of the spinal cord was measured in 2 studies (9%) [58,59]. Volume [52], sagittal diameter [57], and deformation [47] were measured in one study each (4%).

*Dynamic simulation*

Two studies (9%) looked at dynamic simulation. One study (4%) modeled the stress distribution of the spinal cord with flexion speeds that varied from 0.5 degrees per second to 50 degrees per second [43]. One study (4%) modeled loading by applying an imposed velocity to the IVD at 0.05 mm/ms for 25 microseconds [56].

## Discussion

There is considerable variability in how FEMs are constructed to study the cervical spinal cord [60–62]. Some models have been simplified to conserve computational power by modeling the spinal cord as a homogenous element while others separated grey and white matter. Ichihara et al. [61]. showed that there is increased rigidity in the grey matter, however, other authors have suggested that there is no significant difference in biomechanical properties between the gray and white matter [63]. Overall, less than 50% of the studies in this review included dura mater, pia mater, and cerebrospinal fluid, which are essential to accurately simulate the biomechanical responses of the spinal cord [64].

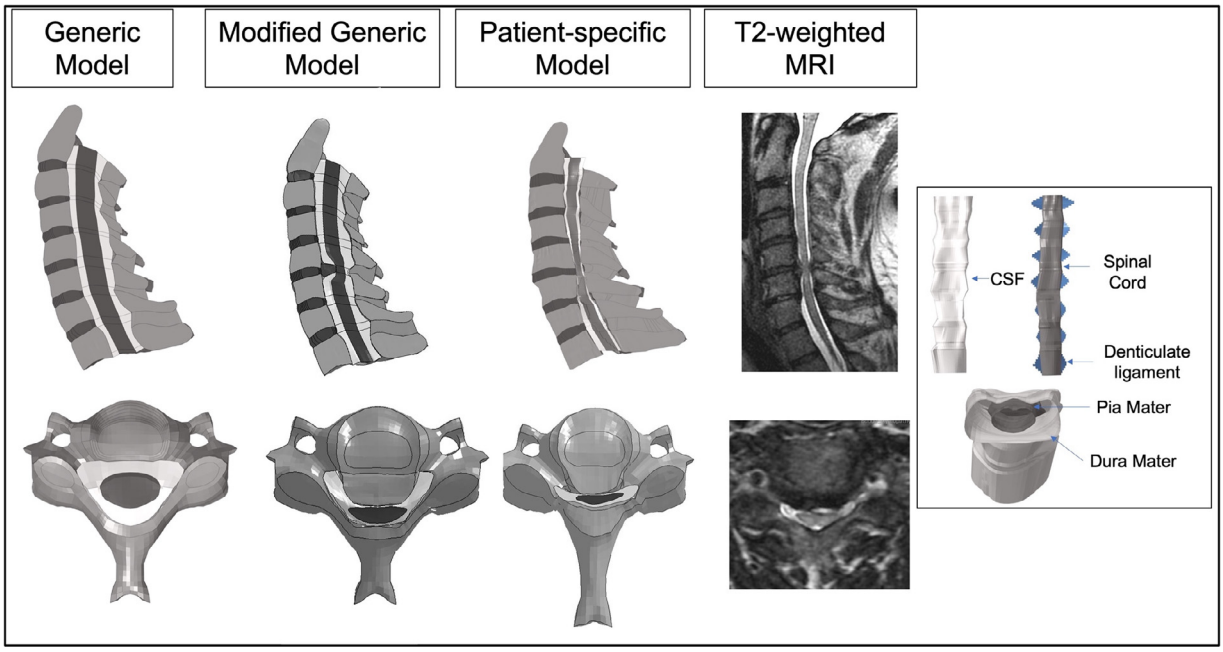


**Fig. 3.** Example of a patient-specific FEM developed from sagittal and axial T2-weighted MRI with individual spinal cord components, and patient-specific spinal cord morphology. Modified generic FEMs include pathology (disk herniation) without incorporating global spinal alignment or geometries. Sagittal and axial (C5–C6 level) generic, modified generic and patient-specific FEMs are compared with show substantial differences in spinal cord morphology.

This highlights the challenge in comparing results between studies and the need for standardization of modeling parameters for human cervical spinal cord FEMs.

In vitro mechanical testing of the human cervical spinal cord shows that the spinal cord exhibits a nonlinear J-shaped elastic response to tensile loading [65], and therefore a quasilinear viscoelastic or hyperelastic model can capture nonlinear material behavior of the spinal cord. Although the majority of studies used a hyperelastic [9,10,41,52,53,56–59] or viscoelastic model [40,43,50,51], 10 studies (44%) measured spinal cord responses using a linear elastic model [7,42,44–49,54,55]. Linear elastic models assume that the material properties of the spinal cord remain constant and the relationship between stress and strain is linear. They are computationally efficient and relatively simple to implement. However, they may not accurately capture the nonlinear behavior of the spinal cord under large deformations or complex loading conditions. Hyperelastic models account for the nonlinear stress-strain relationship exhibited by the spinal cord. These models can provide a more accurate representation of the mechanical response of the spinal cord under various loading conditions. However, they can be computationally demanding and require accurate material parameters, which may not always be available. Viscoelastic models incorporate both elastic and viscous properties, capturing the time-dependent behavior of the spinal cord. These models can simulate the response of the spinal cord to dynamic loading conditions, such as impacts or cyclic loads. The main limitation of viscoelastic models is their increased complexity and the need for additional material parameters, which can be difficult to obtain experimentally. The optimal model for the spinal cord would be one that balances accuracy, computational efficiency, ease of implementation and would depend on the specific research question or clinical application being addressed. The complexity of the spinal cord, which includes white matter, gray matter, and blood vessels, makes it difficult to create an accurate model. The consequences of assuming a homogeneous model may reduce accuracy, loss of material-specific behavior, and inadequate representation of load distribution. Homogeneous models assume uniform material properties, oversimplifying the complex and varied nature of biological tissues, leading to inaccurate prediction of biomechanical response. However, creating a heterogeneous model demands more detailed input data, heightened computational power, and validation through experimental evidence. When deciding between homogeneous and heterogeneous models, it is important to consider the trade-offs between simplicity and accuracy, depending on the study's specific goals and requirements.

At present, there is no consensus on the type of metric (eg, peak von Mises stress) that best explains the response of the cord to physiological loading. Different metrics have been employed depending on the specific application and desired outcomes. Common biomechanical outputs include stress, strain, displacement, pressure, spinal cord diameter, and cross-sectional area. Clinicians often use spinal cord diameter and cross-sectional area to quantify spinal cord compression, as these can be measured using MRI. Experimental studies investigating the spinal cord's mechanical responses under mechanical loading are limited; however, they often focus on changes in length and the resulting strain. Computational research typically uses stress and strain outputs to examine the spinal cord's mechanical response under various loading conditions. These outputs help understand intrinsic responses and identify regions susceptible to injury. The choice of output is driven by the need to validate the model against experimental data or compare results with previous studies. Ultimately, the choice of output hinges on the specific application, availability of experimental data for validation, desired outcomes, and limitations of the FEM design. Enhancing our understanding of the relationships between various metrics and their applicability in different contexts will support the development of more accurate and effective spinal cord models.

Finite element modeling can simulate surgical interventions and predict the effect of surgery on spinal cord biomechanics. This can be useful in determining whether a surgical intervention improves the dynamic stress and strain within the spinal cord. Stoner et al. [10] compared spinal cord stress and strain outputs for anterior cervical diskectomy and fusion, anterior cervical diskectomy and fusion with laminectomy, and double-door laminoplasty. The authors found that all surgical techniques reduced spinal cord stress/strain at the surgical site, but only the anterior cervical diskectomy and fusion model was associated with increased adjacent segment spinal cord stress. A recent study by Vedantam et al. [13] also confirmed increased adjacent segment spinal cord

stress after anterior cervical diskectomy and fusion, which was greater in multilevel compared with single level fusion. Together, these studies highlight the utility of FEM in simulating treatment paradigms and associated cervical spinal cord responses.

The use of patient-specific data in FEM development is essential to accurately define intrinsic spinal cord forces for the individual patient and this approach is needed to enhance clinical translation. Computed tomography imaging provides excellent contrast for bony anatomy; however, spinal cord anatomy and contents of the vertebral canal are best visualized on MRI. Magnetic resonance imaging-derived spinal cord geometries, therefore, are necessary to create accurate patient-specific spinal cord FEMs (Fig. 3). Additionally, the inclusion of all structures in the spinal canal (dura mater, pia mater, cerebrospinal fluid, ligamentum flavum, and posterior longitudinal ligament) is necessary to accurately estimate spinal cord responses. Automated segmentation and meshing from presurgical magnetic resonance imaging will be integral to optimizing and accelerating spinal cord FEM development for clinical use. In addition to incorporating patient-specific geometries, future models will need to use individualized cervical spine range of motion (measured using dynamic x-rays or goniometers) to determine simulated dynamic forces.

Although FEMs of the human spinal cord incorporate diverse anatomical structures, they are several limitations to this approach. Limitations of the FEM approach to study spinal cord biomechanics include software accessibility, cost, and expertise required to develop and run the models. While the dimensions and tissue properties can be adapted from prior studies, commonly used FE software packages are not open source and software license costs remain a barrier to widespread use of this technique. Generation of accurate spinal cord FE models require knowledge of anatomy, mechanics, and material science. Optimal computational processing power is necessary to generate FEMs. Importantly, input from physicians is necessary to ensure clinical relevance and utility. In vivo validation of all stress and strain outputs is not feasible in humans. Stoner et al. [10] described MRI-derived measurement of cervical spinal cord strain, yet other outputs including stress could not be measured. Magnetic resonance imaging-derived measurements cannot be applied to traumatic spinal cord injury with spinal instability, severe spinal cord compression, or patients with limited neck range of motion. Currently, tissue material properties of the white and gray matter of the human spinal cord are not available. Chronic spinal cord compression is known to cause myelomalacia and a change in tissue properties of the spinal cord parenchyma. Accurately quantifying the change in tissue properties due to pathology may impact how accurately FEM outputs reflect true stress and strain in the spinal cord. Most importantly, it is necessary to determine how spinal cord FEM outputs correlate with the patient's clinical status as well as clinical outcomes after surgery or trauma. This further emphasizes the need for patient-specific FEMs over generic and simulated pathological models.

## Conclusion

This review describes the current role of human cervical spinal cord FEM in studying spinal cord stress and strain states in the presence of cervical spinal cord pathology. There is considerable variation in anatomical structures and tissue material properties included in spinal cord model development. Current cervical spinal cord FEMs, however, do not include patient-specific spinal cord geometries. This review is an important addition to the literature and focuses on an innovative advancement of the finite element technique that is not routinely studied. Our review also provides guidance on areas of improvement as well as limitations that will need to be overcome in the future. Spinal cord FEMs provide a unique insight into biomechanical spinal cord responses in pathological states, and can supplement conventional clinical imaging. Improvements in automated model development and the inclusion of patient-specific data are expected to improve the generalizability and clinical translation of this technique.

## Funding

This study was supported by AO Spine North America, North American Spine Society.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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