

## Finite Element Analysis of Laminoplasty in Cervical Spine Biomechanics

### Abstract

**Background:** This study compares the biomechanical behavior of individuals before and after laminoplasty surgery to evaluate the capability of finite element modeling in facilitating the diagnosis, treatment, and prevention of cervical spine injuries. It also aims to standardize surgical procedures and reduce complications in patients. The main objective of this research is to develop a personalized parametric finite element model to predict the biomechanics of the cervical spine in patients post-laminoplasty.

**Materials and Methods:** A personalized parametric geometric model based on 16 anatomical parameters, extracted from patient radiographs, was created. The study utilized Mimics 2012 software to compile 2D CT scan images into point clouds, followed by initial corrections. Geomagic Studio 2012 software was used for further corrections, surface modeling, and the creation of 3D models. Once all the neck tissues were modeled, the data was imported into Abaqus 2012 for finite element analysis and simulation of the cervical spine. The study focused on creating a highly accurate geometric model of the volumetric tissues, as well as ligaments and muscles, to establish a suitable foundation for future research on material properties and tissue behavior without geometric model concerns.

**Results:** While the analysis of laminoplasty in cervical spine biomechanics required validation in terms of flexion and extension, any loading outside the midsagittal plane also needed corresponding validation. The validation of the motion response for the disc between the second and third vertebrae was performed, and consistent design across intervertebral discs allowed the omission of additional motion response calculations. The good alignment of the range of motion in extension torque application is attributed to the correct design of the facet joints and the appropriate spacing between the facet cartilages in the current model.

**Conclusion:** In the natural state of the human body, the primary role of supporting the head's weight and dissipating energy from compressive loads is assigned to the nucleus of the disc. Although the effects of weight were ignored during the analysis of laminoplasty in cervical spine biomechanics, the mass of spinal and skull tissues resulted in compressive loads along the Z-axis, increasing significantly from top to bottom. Another notable point for the nucleus of the discs is the significant impact of its viscoelastic properties. The modulus of elasticity for the disc nucleus was set at approximately 12 kPa, relatively low compared to other soft tissue properties. However, due to the high strain rate in most tissues, including the disc nucleus, during laminoplasty analysis, the disc nuclei experienced stresses of up to 20 MPa, despite not undergoing severe deformation.

**Keywords:** Finite Element Analysis, Cervical Spine, Laminoplasty, Biomechanics

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### Introduction

The cervical spine consists of seven vertebrae, each composed of a vertebral body connected to a bony ring posteriorly. These vertebrae span from the lowest vertebra, T1, to the highest, C2 (Figure 1). An intervertebral disc sits between the bodies of the upper and lower vertebrae, enabling movement and acting as a shock absorber for the spine. Narrowing of the spinal canal can lead to pressure on the spinal cord<sup>(1)</sup>. Typically, the space within the spinal canal is more than sufficient for the spinal cord. Initial narrowing without compressing the spinal cord usually causes no issues. However, as the narrowing intensifies and pressure is exerted on the spinal cord from the sides, symptoms can appear, known as myelopathy<sup>(2)</sup>.

Spinal canal stenosis can arise from various causes. One of these is congenital stenosis. In these patients, the spinal canal is narrow from birth, though they typically do not have any significant problems initially. However, they may develop symptoms with even minor injuries to the neck. As they age, the spinal

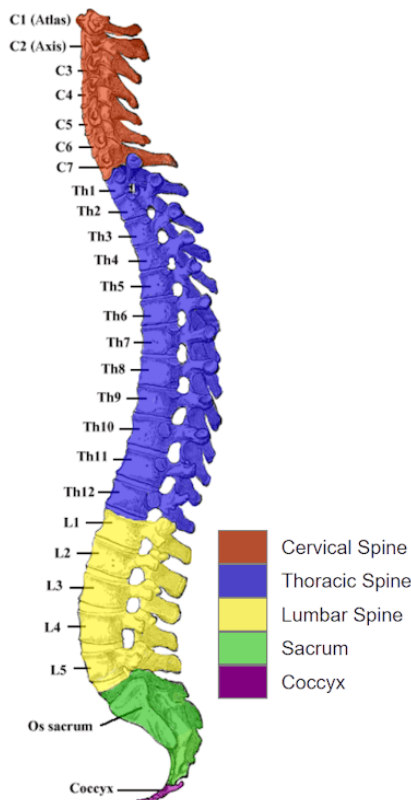


Figure 1. View of Spinal Cords

canal becomes narrower, leading to increased issues. With aging, bone spurs grow from the vertebral body's ring into the canal, further narrowing the internal space.

In 2005, "An" developed a nonlinear dynamic model of six cervical vertebrae of the human spine. Considering that helicopter pilots use heavy helmets, which include weights and specialized equipment, this model was developed to simulate the cervical region and calculate the loads and forces on the intervertebral discs during different flight conditions. The model, created in the ADAMS software, included vertebrae, ligaments, and intervertebral discs. It studied the loads on the neck under bending, extension, lateral bending, and head rotation, evaluating various conditions with and without helmets for the cervical spine<sup>(4,5)</sup>.

In 1999, Deng and colleagues developed a model that, unlike most previous full cervical spine models, included more detailed representations of various tissues in the upper cervical spine region. In their model, most soft tissues were modeled with viscoelastic properties, and the fibers of the discs were represented using a membrane composite model<sup>(6)</sup>. Notably, the active forces of muscles were also included in this model. The model simulated the

movement and acceleration values of the skull under a frontal crash with an acceleration of 12 m/s<sup>2</sup>, after partial spinal loading in quasi-static conditions, using the accelerations and rotations obtained for the first thoracic vertebra from experimental crash tests<sup>(7,8)</sup>. Figure 2 shows the complete image of spinal cords.

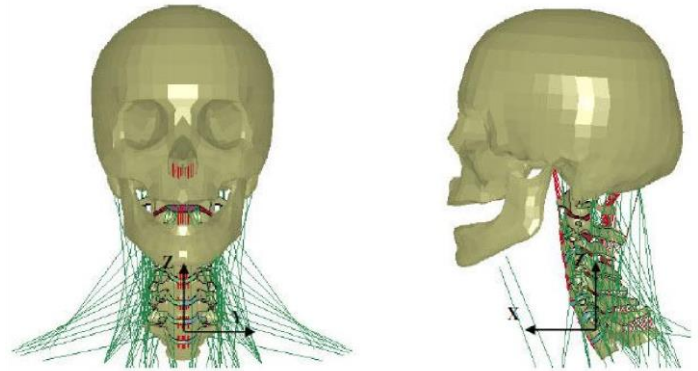


Figure 2. Complete Model of Spinal Cords

In 2005, Holsafel conducted experiments to determine the properties of the layers within intervertebral discs. He studied 11 cadaveric disc samples extracted from the first and second lumbar vertebrae of recently deceased individuals. Each disc was split in half along the sagittal plane: one half was used for tensile testing of the single-layer annulus in the fiber direction, and the other half was used to measure the angles of the fibers within the disc layers. Ultimately, he provided a one-part graph for the elastic properties of the disc fibers, with a modulus of elasticity ranging from 28 to 78 MPa, increasing with higher strain values<sup>(9)</sup>.

In his study, "Lee" separated the ALL and LF ligaments from seven cadavers, analyzing a total of 32 ALL ligaments and 12 LF ligaments using various protocols to degrade them before conducting tensile tests. He selected these ligaments due to their significant impact on spinal function, differences in elastin and collagen content, and their common involvement in whiplash injuries<sup>(10)</sup>.

Due to the complex musculoskeletal structure, the human cervical spine is one of the most challenging areas for developing biomechanical modeling<sup>(11)</sup>. Finite element modeling can help researchers determine internal stresses and pressures in bones, ligaments, and soft tissues, and is widely used for spinal biomechanics research. It also aids in the diagnosis, treatment, and prevention of cervical spine injuries. This study compares the biomechanical behavior of individuals before and

after laminoplasty surgery to assess the utility of finite element modeling in facilitating diagnostic, therapeutic, and preventive technologies for cervical spine injuries and its role in standardizing surgery and reducing complications in patients.

Finite element simulation and modeling are proposed as suitable tools. These simulations are repeatable and allow for the optimization of product designs or detailed aspects based on this method<sup>(12)</sup>. The primary goal of this research is to develop a personalized parametric finite element model of patients to predict the biomechanics of the cervical spine after laminoplasty surgery. For this purpose, a personalized parametric geometric model based on sixteen anatomical parameters extracted from the patient's radiographic images was created. One of the differences and advantages of this study over previous biomechanical works is the use of radiographic images in both the anterior-posterior and lateral views, which allows for faster updates with suitable accuracy compared to precise models concerning each patient's anatomical parameters.

## Research Methodology

In this study, all anatomical dimensions were directly extracted from each person's radiographic images to increase modeling accuracy, using separate software for designing and analyzing each part. The cervical spine's vertebrae geometry was obtained using individual CT scan images. Then, using the vertebral surfaces, the intervertebral soft tissues were modeled. The model was then imported into finite element software, where ligaments and muscles were added to the assembled vertebrae, followed by the meshing and validation process in the software. The Mimics 2012 software was used to aggregate the 2D CT scan images and convert them into point clouds for initial adjustments. Geomagic Studio 2012 was used for correction, surfacing, and ultimately creating 3D models. After modeling all the neck tissues, the model was imported into the Abaqus 2012 finite element software, where the cervical spine's simulation and analysis were conducted.

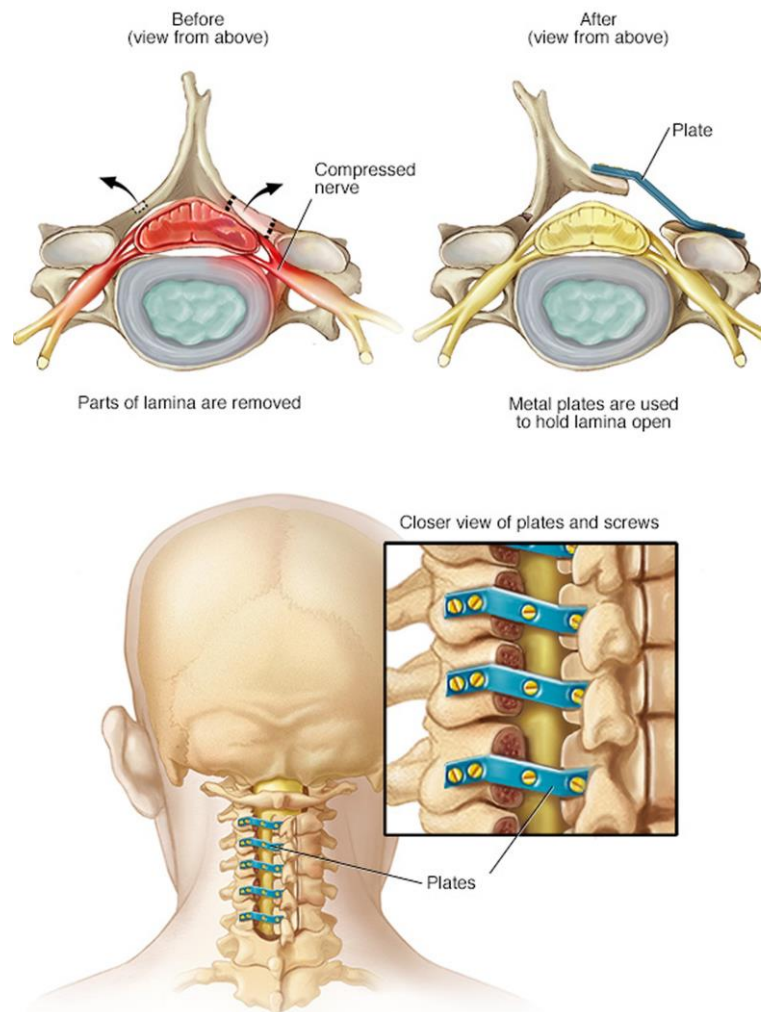
Initially, considering the age, gender, height, and weight of the individuals studied and the models used in previous studies (corresponding to 50th percentile males), the goal was to find CT scan images of a 25-year-old man with a height of about 170 cm and weight of about 70 kg. After field searches in several hospitals, CT scan images of a 30-

year-old individual with a height of 178 cm and weight of 82 kg were selected as the best choice for the model's foundation at Hazrat Rasool Akram Hospital in Tehran. It is noteworthy that the individual underwent a CT scan due to spinal canal stenosis on the recommendation of their physician and did not receive radiation for the current research, thus not requiring a consent form. Only the CT images and physiological characteristics were provided for this study.

The CT scanner used had 42 slices, which is not considered high quality, but this quality primarily affects the differentiation between soft and hard tissues. The resulting CT images comprised 294 images covering the entire cervical spine area with one-millimeter axial slices. An essential parameter in these CT images was having closely spaced sections. The images were imported into the Mimics software, where bone tissues were separated from other tissues, resulting in a 3D point cloud of all seven cervical vertebrae, including the first thoracic vertebra and the lower part of the skull, totaling 411,262 points. The point cloud was imported into Geomagic Studio 2012, where, after some corrections, it was converted into 603,126 triangular meshes representing the vertebrae's geometry. This marked the beginning of the main process for obtaining the cervical spine's geometry. The sagittal, frontal, and axial planes were aligned with the standard Z-X, Y-Z, and X-Y planes, respectively. The leftward deviation of the cervical vertebrae due to improper head rotation was corrected. Notably, the right half of the spine and areas near the sagittal plane were corrected throughout the process, and the left half of all models was created by mirroring the right half relative to the sagittal plane.

The analyses included measuring the range of motion of the vertebrae relative to each other in the partial spinal model to validate the model and apply loading due to spinal canal stenosis. Stress results for the tissues and changes in acceleration and displacement for the center of mass of the skull and vertebral centers of mass were presented.

In the analysis of the laminoplasty procedure, a hinge is created on the lamina layer, opening up the spinal canal space. A metal piece is then placed over the gap in the opened section of the spine, reducing pressure on the spinal cord (Figure 3). For analyzing the current model, all degrees of freedom at the center of mass of vertebra T1 were fixed during the analysis, and the acceleration provided along the



**Figure 3 - The Laminoplasty Procedure**

horizontal axis was applied to the center of mass of the same vertebra.

For analyzing the laminoplasty procedure, the entire model was initially subjected to the applied loading as described above. However, during the early stages of the analysis, the software encountered an error labeled as "Error Code 1," an internal software error that halted the analysis. Upon investigation, it was determined that this error is often due to hardware limitations or internal coding discrepancies within the software, possibly due to its closed-source nature. Consequently, several simplifications were made to the geometry and material properties. Muscles and ligaments were removed from the model, the viscoelastic properties of the facet cartilage were not defined, and the elasticity of the disc fibers was simplified from nonlinear to linear. Table (1) shows the properties of the facet cartilage and disc fibers.

Additionally, due to the removal of muscles and ligaments, which consequently reduced the system's resistance to tensile loads, the mass of the head

(approximately 1200 grams) was considered about one-third of the real value and distributed along the spine. The study continues with the presentation of the effects of stress and strain resulting from the applied acceleration on various tissues, the acceleration of the center of mass of the skull and vertebrae, the skull movement profile during laminoplasty, the relative movement of the vertebrae, and other aspects.

## Results

The motion response of the cervical spine and skull is visually depicted in Figure 4. The cervical spine reaches its maximum flexion at 5.7 seconds, after which the speed of the skull relative to the T1 vertebra becomes positive, reaching its maximum extension at 32.5 seconds. Subsequently, around 2.5 seconds, the kinetic energy of the system decreases, and the neck returns to its normal state.

The acceleration experienced by the vertebrae and skull is noteworthy. Figure 5 shows the acceleration

Table 1: Modified Properties for Collision Analysis			
Facet Cartilages	Linear Elastic	E=9.9453MPa	$\nu = 0.49$
Matrix Fibers	Linear Elastic	E=450MPa	
	Layer thickness= 0.17	Bar distance: 0.23	Area per bar= 0.0112155

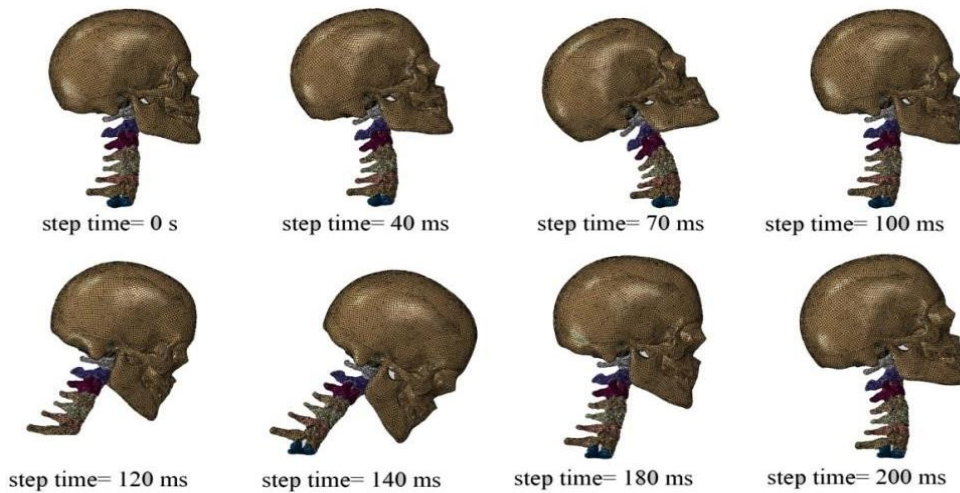


Figure 4 - Visual representation of cervical spine and skull movement

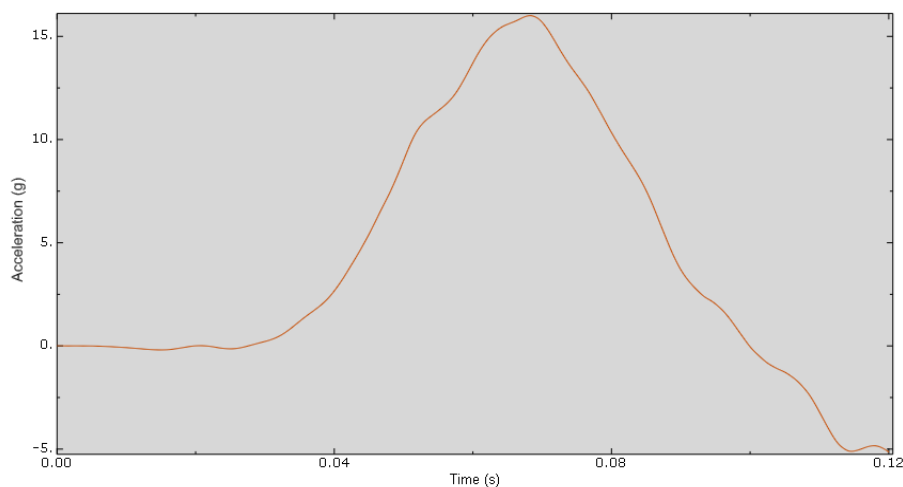


Figure 5 - Acceleration of the skull's center along the x-axis

of the skull's center of mass, and Figure 6 displays the acceleration of the centers of mass of the vertebrae along the x-axis. The maximum acceleration applied to the skull's center of mass during extension is 17.24g, occurring at 67 milliseconds.

During neck flexion, the discs compress at the anterior side and stretch at the posterior side; this occurrence reverses during extension. As a result, the vertebrae rotate relative to each other, leading to the overall flexion or extension of the neck. All soft tissues, including cartilage, discs, endplates,

nucleus pulposus, and annulus fibrosus, experience stress during the analysis. We will discuss the extent and distribution of stress within these tissues. The highest stress among the facet joint cartilages occurs in the C7-T1 facet cartilage, reaching a maximum of 5700 kPa at 82 milliseconds.

The discs facilitate the rotation of the vertebrae relative to each other during flexion and extension, designed precisely for this function. The maximum stress in the annulus fibrosus during flexion is 255 kPa, occurring in the disc between the C6 and C7 vertebrae. Generally, the stress in the upper discs is

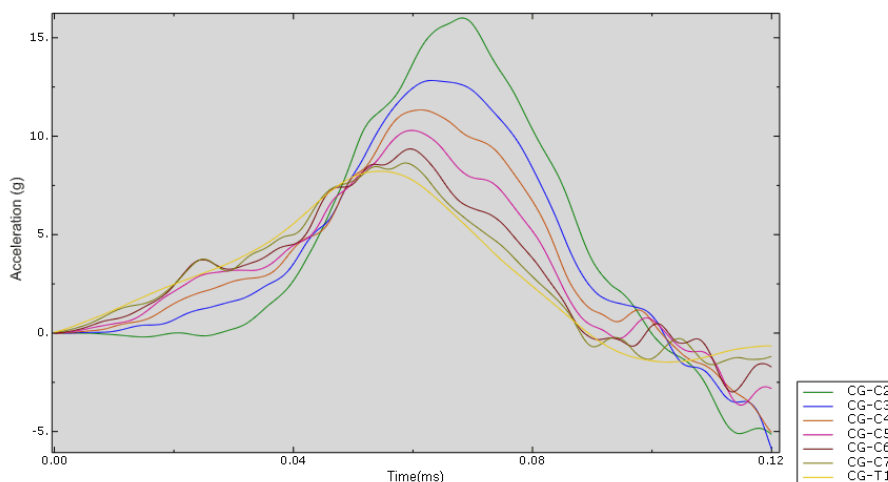


Figure 6 - Acceleration of the vertebrae's centers of mass along the x-axis

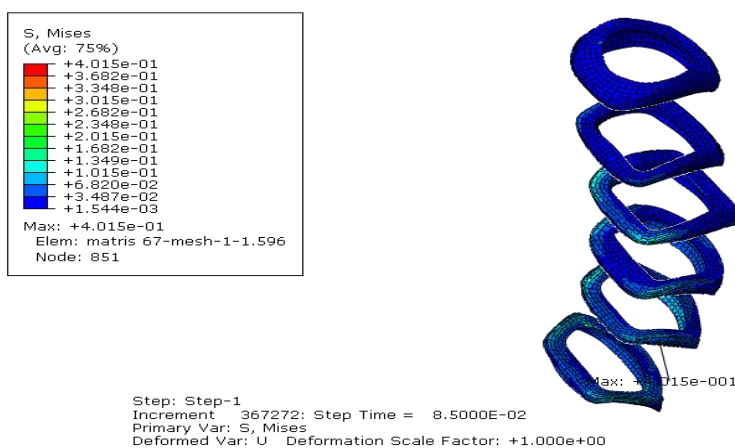


Figure 7 - Stress distribution in the discs

lower than in the lower discs. Figure 7 shows the stress distribution across all discs.

The nucleus pulposus experiences similar conditions to the annulus fibrosus, with stress distribution decreasing as one moves from the lower discs to the upper discs at any given time during the analysis.

## Discussion

In previous studies<sup>(6-10)</sup>, due to the numerous issues related to the high number of tissues, modeling complexities, and the high computational cost of complete cervical spine models, fewer finite element models exist. Most comprehensive cervical spine modeling studies utilize multi-body models.

In the current study, a finite element model of the laminoplasty procedure in the biomechanics of the complete cervical spine, comprising all tissues involved in the mechanical function of the cervical spine, was developed. Given that most

previous studies featured geometrically flawed comprehensive cervical spine models, which ultimately caused errors in the analysis responses, the current study focused on creating an accurate geometric model. This effort aimed to provide a reliable foundation for future studies on material properties and tissue behavior, free from the geometric issues of the model. Notably, the modeling employed radiographic images from both the anteroposterior and lateral views, offering faster and appropriately accurate updates relative to each patient's anatomical parameters.

The study also aimed to define and apply material properties for various tissues, emphasizing the importance of hyperelastic and viscoelastic properties due to the living tissues involved. However, due to software limitations and time constraints, further simplifications were made during the analysis phase. This section will review the findings from the analyses and provide suggestions for future work.

Considering that the analysis of the laminoplasty procedure in cervical spine biomechanics required validation of the model in flexion and extension directions, additional validation in other directions would be necessary if the loading were outside the mid-sagittal plane. Validation of disc motion response was conducted for the disc between the second and third vertebrae, with the design uniformity allowing for generalization to other discs. The maximum acceleration of the vertebrae's centers of mass increases from the lowest to the highest vertebra, corresponding to the increased distance from the T1 vertebra. This acceleration sequence, with a short delay of about 32 milliseconds caused by disc deformation, reaches from the lowest (T1) to the highest vertebra (C2).

As previously noted, the upper vertebrae experience greater acceleration than the lower vertebrae, indicating that the force applied to the lower discs is greater. This leads to more significant deformation of the lower discs and relative rotation of the vertebrae. Laminoplasty may be indicated in patients with myelopathy and multi-level spondylosis, such as congenital stenosis. Severe spinal stenosis can lead to various symptoms, including pain, weakness in the arms and/or legs, and instability in walking (myelopathy).

In the natural state, the primary function of the human body is to support the head's weight and absorb the energy from compressive loads, primarily handled by the disc nucleus. Although the effects of weight were disregarded during the analysis of the laminoplasty procedure in cervical spine biomechanics, the masses of the spinal tissues and skull resulted in compressive loads on the discs, increasing noticeably from top to bottom. Another noteworthy point for the disc nucleus is the significant impact of its viscoelastic property. The elasticity modulus for the disc nucleus was defined and applied as approximately 12 kPa, a relatively low value compared to other soft tissue properties. However, due to the high strain rates in most tissues, including the disc nucleus, during the laminoplasty procedure in cervical spine biomechanics, the disc nuclei endured stresses of about 20 MPa, despite not undergoing severe deformation.

For future research, it is suggested that, as the input acceleration of the first thoracic vertebra in the current study was sourced from another study, future studies could utilize skull accelerations and other outputs in cervical spine analysis to examine intracranial tissues. Given the modeling work, the

influence of uncovertebral joints under various loading conditions can be explored, a subject with limited studies thus far. The impact of replacing natural discs with artificial ones, fixing two or more vertebrae relative to each other following surgical interventions on the cervical spine, and similar scenarios can also be examined for their effects on cervical spine function under different loading conditions.

## References

1. Panzer M. Numerical modelling of the human cervical spine in frontal impact [Internet]. University of Waterloo; 2006. Available from: <https://uwspace.uwaterloo.ca/handle/10012/2865>.
2. Fice JB. Numerical modeling of whiplash injury [Internet]. University of Waterloo; 2010. Available from: <https://uwspace.uwaterloo.ca/handle/10012/5636>
3. Langtree IC. Human spine and spinal cord C1 to S5 vertebra [Internet]. Disabled World. 2017. Available from: <https://www.disabled-world.com/disability/types/spinal/spine-picture.php>.
4. Ahn H. A virtual model of the human cervical spine for physics-based simulation and applications [Internet]. University of Tennessee Health Science Center; 2017. Available from: <http://dx.doi.org/10.21007/etd.cghs.2005.0008>.
5. Fathollahi H. Multi-body dynamic analysis of cervical spine for helicopter pilots [Internet]. 2021. Available from: <http://dx.doi.org/10.32920/ryerson.14663169.v1>.
6. Liu Y-CDXL. Modeling of the Human Cervical Spine Using Finite Element Techniques [Internet]. Sae.org. 1999. Available from: <http://dx.doi.org/10.4271/1999-01-1310>.
7. Defense technical information center [Internet]. Dtic.mil. [cited 2024 Jul 7]. Available from: <https://apps.dtic.mil/sti/citations/ADA284358>.
8. J. Thunnissen, J. Wismans, C. L. Ewing, D. J. Thomas. Human Volunteer Head-Neck Response in Frontal Flexion: A New Analysis [Internet]. Sae.org. 1995. Available from: <http://dx.doi.org/10.4271/952721>.
9. Holzapfel GA, Schulze-Bauer CAJ, Feigl G, Regitnig P. Single lamellar mechanics of the human lumbar anulus fibrosus. *Biomech Model Mechanobiol* [Internet]. 2005 [cited 2024 Jul 7];3(3):125–40. Available from: <http://dx.doi.org/10.1007/s10237-004-0053-8>.
10. Devin Leahy P, Puttlitz CM. The effects of ligamentous injury in the human lower cervical spine. *J Biomech* [Internet]. 2012 [cited 2024 Jul 7];45(15):2668–72. Available from: <http://dx.doi.org/10.1016/j.jbiomech.2012.08.012>.
11. Alizadeh MH. Epidemiology of head, neck and torso injuries in taekwondo, karate and judo. *Feyz Medical Sciences Journal* 2012 [Internet]. 2012;16(4):368–85. Available from: <https://feyz.kaums.ac.ir/article-1-1561-en.html>.
12. Nikkhoo M. Analysis of the Effects of Trauma on the Biomechanical Behavior of the Cervical Spine Based on Finite Element Modeling. *IRANIAN JOURNAL OF ORTHOPAEDIC SURGERY* [Internet]. 2021; Available from: <https://www.sid.ir/paper/1010859/en>.