

Numerical Modelling of the Behaviour of the Cervical Spine under the Effect of a Flexion / Extension

N DAMBA^{1, 2}, A OUDRANE¹, B AOUR², M S BENNOUNA², N BELKAHELLA²

¹Department of Science and Technology, Faculty of Science and Technology, Ahmed Daria University of Adrar, 01000, (Algeria).

²Laboratory of Applied Biomechanics and Biomaterials (LABAB), B.P: 1523 El Mnaour, ENPO-MA, 31000, Oran, (Algeria).

*Corresponding author; Email: boudjmaa.damba@yahoo.fr nad.damba@univ-adrar.dz

Article Info

Article history:

Received 30 July 2019

Revised 28 September 2019

Accepted 07 November 2019

Keywords:

Biomechanics
Cervical Spine
Intervertebral Disc
FEM
Hyper elasticity
Ligaments

ABSTRACT

Numerical simulation is today widely used in several fields of engineering, and research undertaken for more than 20 years concerning the geometric and mechanical modeling of the spine gradually leads to clinical applications of major interest. Indeed, the in vivo and in vitro evaluation tools pose a certain number of limitations: non-standardized procedures and inter-specimen variability for in vitro tests, medical, ethical constraints, and inter-individual variability for in vivo. These limitations are actually obstacles to comparison. It is notably within the framework of implant comparisons that the methods of structural calculation, and more particularly finite element modeling, widely used in classical mechanics, find their usefulness. In this context, this present work consists in developing a three-dimensional model of the cervical spine, in order to subsequently optimize the fitting of disc prostheses.

I. Introduction

The lesion of the cervical spine represents 50.7% of the total trauma due to car accidents and the two upper functional units C2-C3 and lower C5-C6 are the most [2]. The study of the response of the cervical spine to moment applied produced by high speed impact conditions such as the ejection of motor vehicle accidents where emergency pilots can provide important results which would contribute to improve safety and event systems to reduce injuries and fatalities. Although specific injury mechanisms are still being explored, several theories link the facets of the joints, the ligaments of the spine, between vertebral discs (IVD), the vertebral arteries, the spinal ganglia, and the neck muscles for possible causes of injury under high speed impact conditions [3]. Numerous experimental and numerical studies have studied the response of the ligaments (devoid of muscles) of the cervical spine.

This study aims to apply the moment load to the spine during sagittal flexion-extension using the finite element method and to know its effect on the soft tissues (the ligaments and discs), and to predict in the future the most vulnerable ligaments or discs in order to take the necessary measures to avoid a health crisis later.

A non-linear three-dimensional model of the C2-C7 segment with a bio-faithful representation of the vertebrae and soft tissues was developed using the Abaqus software (Inc., ABAQUS 2014). The properties of nonlinear materials which represent the effect of the strain rate, and the viscoelastic behavior of the ligaments have been used. This model has been validated for the quasi static loading conditions.[4-12]

II. THE MECHANICAL PROPERTIES OF THE COMPONENTS

II.1 Intervertebral disc

The disc was governed by a Mooney-Rivlin type hyper-elastic behavior law of the following form:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + K(J - 3)^2 \quad (1)$$

Where C10, C01 and C11, are the Mooney-Rivlin constants characterizing the material.

I1, I2 are the first and second invariants of the deviatoric strain tensor.

The properties of the materials by the bone and the disc are presented in Table 1.

Table 1. Properties of materials for the different components of the functional unit.

Description	Element Type	Young Module (MPa)	Poisson Coefficient
Vertebral Bone	4 node shell of type S4R	10000	0.29
Nucleus Pulposus	4-node tetrahedron of type C3D4	C01=0.56 C10=0.14	0.45
Annulus Fibrosus		C01=0.12 C10=0.09	0.49

II.2 The ligaments

The ligaments (ALL), (PLL), (CL), (SLL), (LF) were governed by a nonlinear viscoelastic law (Rohlmann et al., 2006). All the material properties of bones and soft tissues have been adapted from previously published studies (see table below).

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

Table 2. Mechanical properties of ligaments.

	ALL	PLL	SLL	LF	LC
Density (kg/mm ²)	1.0 E-06	1.0 E-06	1.0 E-06	1.0 E-06	1.0 E-06
Young's Module (MPa)	11.4	9.12	4.56	4.56	22.8
Poisson Coefficient	0.4	0.4	0.4	0.4	0.4
Tangent module (MPa)	10.0	9.0	4	4.0	22.0
Viscosity Coefficient	28	28	28	28	28
Navier Constant	1.0 E06	1.0 E06	1.0 E06	1.0 E06	1.0 E06

II.3 3D Mesh of Cervical Components

As shown in Figure 1 and Figure 2, the various components have been meshed in linear elements tetrahedral with 4 nodes or hexahedral with 8 nodes, since the interfaces of contact (bone-cartilage, cartilage-disc, bone-ligaments)

are subjected with the stresses and strains more than the other surfaces under the action all the types of loadings applied, one judged fundamental to refine the mesh of our model.



Figure 1. 3D finite element modeling of the vertebrae of the cervical spine.



Figure 2. 3D finite element modeling of intervertebral discs.

II.4 Boundary Conditions

In order to define the boundary conditions, a restriction on the movements of translation and rotation of the spine was applied whose base surface of C6 is (zero displacements). Several loads in all directions (anterior, posterior, lateral (left and right)) were applied as follows: [13]

- The application of the load on the upper face of the atlas.
- The fixed part applied to the body of the sixth vertebra (Figure 3).



Figure 3. Application of boundary conditions.

III. Results and Discussions

III.1 Ligaments

When the spine rotates forward in the sagittal plane, it is called flexion, and when it spins backward in the sagittal plane, it is called extension. For either of these two rotations, certain ligaments play an important role in limiting movement. The application of a moment of a value of 2 Nm causes stresses in the ligaments, when they tried to limit the movement, and these stress values vary according to the moment applied and their position on the spine.

This work's results. Present the constraints in all the ligaments in the region of the cervical spine. The following graphs show the evolution of the constraints for the Fifth Cervical Stages.

The anterior longitudinal ligament (ALL) is located on the anterior side of the vertebral body. As the spine rotates in extension, the ligament stretches and thus develops a stress, while in flexion has no contribution of stress, and very small stresses develop in the ligament at the points of junction with the vertebra. Figure 4 shows the development of stresses in the ALL ligament for the five cervical segments.

From Fig. 4, it can be noted that the ALL ligament is very active in extension, while it has almost no contribution at the time of resistant flexion. The highest stress is recorded respectively in the segment C5-C6, then C3-C4 and C1-C2. There is a decrease in stress in the C4-C5 and C2-C3 segments of the spine.[14-15]

A weak stress is detected in flexion movement and this is due to the distal and proximal translation of the vertebrae.

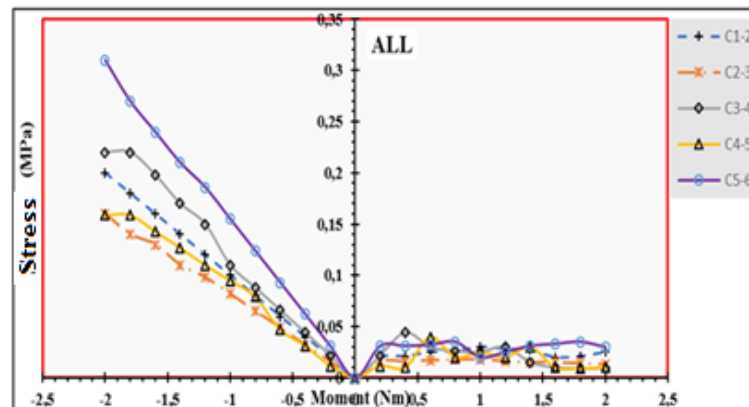


Figure 4. Distribution of stresses as a function of time at the ALL ligament level for the C1-C6 cervical segments during Flexion / Extension stresses.

The next ligament to study is the posterior longitudinal ligament (PLL). According to Figure 1, it is located on the posterior surface of the vertebral body, near the longitudinal line which crosses the vertebrae in posterior and anterior sections. Theoretically, it helps to resist moments of flexion and extension, but it is more predominant in flexion. Figure 5 shows the evolution of stresses on the PLL ligament under the action of flexion-extension rotations.

According to figure 5, the PLL helps to limit the rotation of the flexion whereas it has practically no contribution to limit the rotation of the extension, even if it is in the Posterior part of the vertebra. The highest stress is located in the movement segments C5-C6 and C3-C4 and C2-C3 where the tension reaches up to 0.15 MPa, 0.14 MPa, and 0.13 MPa successively. The stress reported in PLL drops significantly in the other segments, as shown in Figure 5. All segments behave the same way in both flexion and extension, although they experience slightly higher stress in flexion.

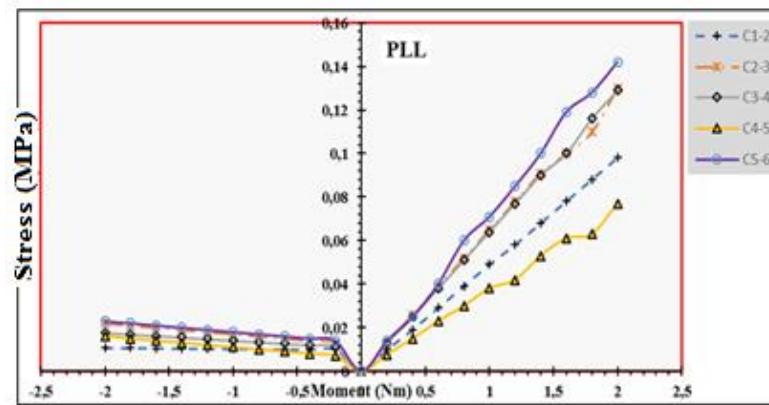


Figure 5. Distribution of stresses as a function of time at the PLL ligament level for the C1-C6 cervical segments during Flexion / Extension stresses.

The capsular ligament (CL) is located around the facet joint on the upper and lower surfaces of a vertebra. According to Figure 6, it rests on the line that crosses the vertebra in two halves. Theoretically, it is involved in limiting flexion and extension rotations.

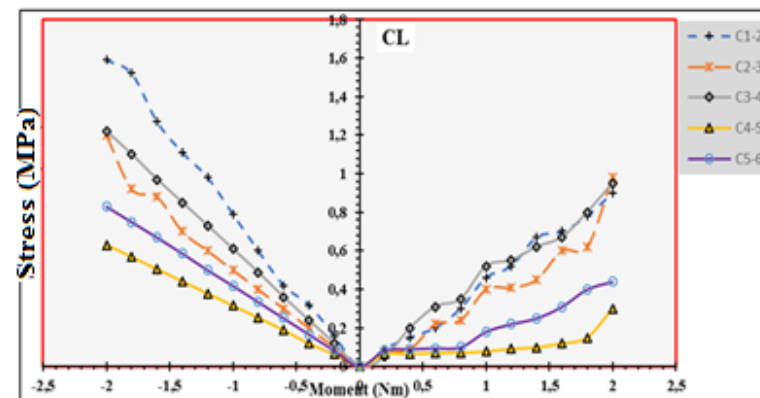


Figure 6. Distribution of stresses as a function of the moment at the level of the ligament CL for the cervical segments C1-C6 during Flexion / Extension stresses.

As proven from Figure 6, CL is active in both flexion and extension. The greatest stresses are developed in the C1-C2 segment by being more involved in resistance to extension than bending. We also note that the CL ligament at different stages of the cervical spine is subjected to stresses in both cases either in flexion or in extension.

Ligament flavum (LV) is located in the posterior region of the vertebra, at a distance close to the longitudinal transection line.[16,17,18]

Depending on its location, LV is mainly active in limiting the flexion movement. Figure 7 shows the distribution of stresses along each ligament for segments C1 to C6.

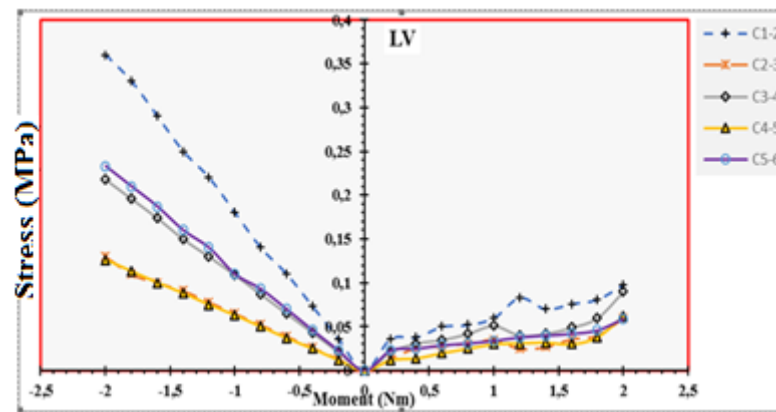


Figure 7. Distribution of the stresses as a function of moment at the flavum ligament level for the C1-C6 cervical segments during flexion / extension stresses.

Similar to the PLL ligament, LV is mainly active in flexural strength and has minimal resistance assistance at the time of extension. Similar to ALL and PLL, the ligaments of the C1-C2, C5-C6 and C3-C4 segments are more involved than the ligaments of the C2-C3 and C4-C5 segments because the upper vertebrae rotate more than the lower vertebrae. [19-24]

However, compared to PLL, LV is not very involved in resistance to flexion-extension rotations, although it is more active in flexion than in extension. The highest value of stress in flexion is approximately 0.35 MPa while it is only 0.15 MPa for the PLL, and its contribution of the stresses decreases by lowering the spine (C3-C4; C4-C5; C5-C6).

The interspinous ligament (ISL) is located at the posterior edge of the vertebrae connecting two adjacent spinous processes together. Due to its location, ISL is only involved in flexion and negligible contribution to the extension. Figure 8 shows the distribution of the stresses on the LSI in the flexion and extension rotations on the five levels of cervical spine.

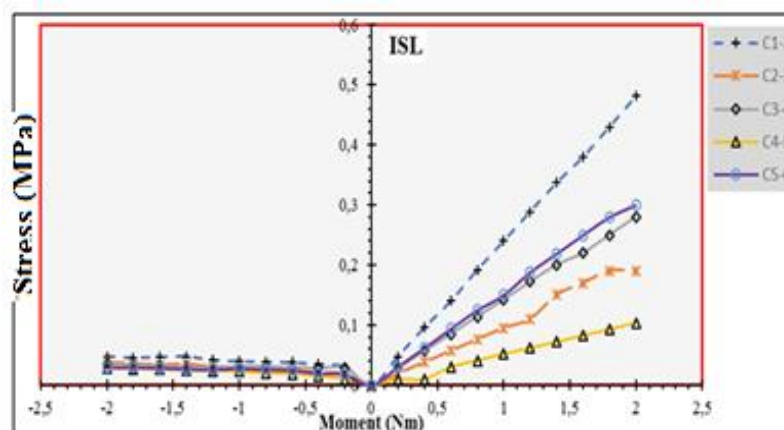


Figure 8. Distribution of stresses as a function of the moment at the interspinous ligament for the C1-C6 cervical segments during Flexion / Extension stresses.

As the spine turns in flexion, ISL stretches while trying to keep the vertebrae in position and limiting movement. This imposes a significant stress on the ligament, as can be seen in Figure 7. A stress of a value of 0.52 MPa is noted on the upper ligament C1-C2 and it weakens as it moves towards levels lower until the detection of a 0.09MPa stress at the level of the lower segment C5-C6. All other segments respond similarly to the bending moment. In extension, all five ligaments have the same response while low stress is detected in the ligaments.

III.2 Intervertebral discs

When the spine moves forward (flexion); the ligaments on the posterior side extend holding the vertebrae in place while limiting the movement of the spine. At a certain point on the anterior part, the vertebra presses on the intervertebral disc, which acts as a load transfer component and helps to resist the load applied. In the case of rotation in flexion, most of the stresses are concentrated at the anterior part of the disc when the vertebral body leans forward and turns, which causes strong compression on the anterior edge, at the same time, the compression force drives the nucleus pulposus on the posterior wall of the disc, which causes strong local stress on the posterior edge. While in extension the compressive force acts on the posterior part of the disc.[25-29]

Entrainment of the nucleus pulposus on the anterior surface of the ring. The following graph (Figure 9) shows the pressure that forms in the nucleus when 2Nm is applied in flexion-extension as well as the force deflected in the fibrous ring as the end of the moment's application.

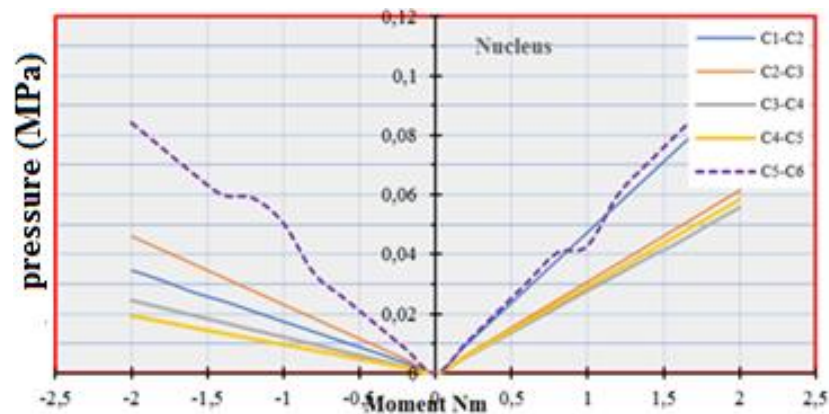


Figure 9. Distribution of stresses along the nucleus pulposus in extension (negative moment) and bending (positive moment).

The intervertebral disc has a different response to the applied flexion-extension moment. According to Fig. 9, the pressure at the core of the segments C5-C6 and C1-C2 in flexion are higher than in extension, which indicates that its contribution to the resistance to resistant flexion is higher than its resistance to resistant extension. The segments C3-C4 and C4-C5 behave in the same way. The tensile force in the fibrous ring reflects the pressure in the nucleus.

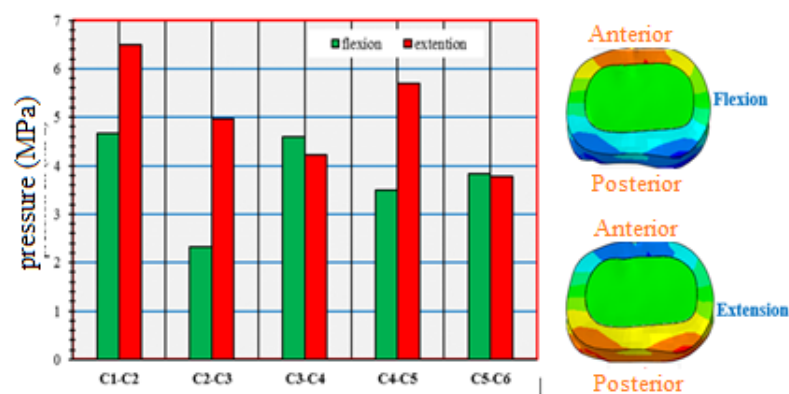


Figure 10. Comparison of pressure stresses at the levels of the fibrous rings for each segment.

We note from figure 10, that the maximum normal stresses in the fibrous ring of the intervertebral discs are concentrated in the segments C1-C2 and C4-C5 which are respectively equal to 6.49MPa and 5.7MPa for the negative rotation (Extension); but for the positive rotation (bending), we note that the maximum stress retained by the same segment C1-C2 is equal to 4.67MPa followed by the segment C3-C4 with a pressure stress of 4.59Mpa, the same figure 10 it is clearly shows that the pressure force level is maximum in the C1-C2 and C3-C4 segments

reaching values of 4.67MPa and 4.59MPa respectively. As for C5-C6, it had the same behavior both in flexion and in extension.

IV. Conclusion

From the results presented in the context of this work, we can draw the following conclusions:

- To perform a bio-faithful modeling, the geometry of the vertebrae must be generated automatically and we must take into account the non-linear behavior of the various components which form the cervical spine.
- The stress concentration (potential site of degeneration of the intervertebral disc) is located in the anterior portion of the fibrous ring in the case of flexion / extension and in the lateral region in the case of lateral flexion.
- In the case of ligaments, it has been found that the concentration of stress will always occur in the capsular ligament.

Finally, it noted that this lowest cervical spine study The C5-C6 segment provides a powerful digital tool that can be easily used to study the biomechanics of disc prostheses of the cervical spine as well as the lesions of the latter. Work on these themes during the development of the spine.

Acknowledgements

We would like to thank the members of the Laboratory of Applied Biomechanics and Biomaterials who helped with this study. I also thank the scientific committee of the Algerian Journal of Renewable Energy and Sustainable Development, also do not forget the directorate General of Scientific Research and Technological Development (DGRSDT) on their contribution and providing them with the appropriate conditions in order to complete this work, which is part of a scientific research project entitled: Development of Bio-faithful models for the biomechanics of joints with and without prostheses (DMBioP).

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How to cite this paper:

Damba N, Oudrane A, Aour B, Bennouna M. S, Belkahella N. Numerical Modelling of the Behaviour of the Cervical Spine under the Effect of a Flexion / Extension. Algerian Journal of Renewable Energy and Sustainable Development, 2019, 1(2),144-153. <https://doi.org/10.46657/ajresd.2019.1.2.4>