Nonlinear finite element analysis of lumbar spine under mechanical load

V Poojara¹, R Trivedi²*, B Modi³ and R Patel⁴

¹Department of Mechanical Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India
²Department of Mechanical Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India
³Department of Mechanical Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India
⁴Health Center, Nirma University, Ahmedabad, Gujarat, India

E-mail: *reena.trivedi@nirmauni.ac.in

Abstract. Nonlinear Finite Element Analysis of lumbar spine is carried out using the optimisation software, to determine the effect of accidents on the human spine under mechanical loading. The lower two lumbar section – L4 and L5 of spinal cord is focussed in the present study. A simplified model of the L4-L5 vertebra was prepared. Bone material was taken as nonlinear and disc centre was modelled as hyper elastic. The ligaments are modelled as 1D truss elements. 2D triangular mesh was generated and converted to 3D tetrahedral mesh. The range of force of 500 N to 1600 N and moment of 7500 Nm was given as an input. The relationship of displacement, stress and strain with force is studied. The analysis was carried out and the results obtained depicted that the force varies depending on the impact of accidents. Conclusions are drawn and the relationship at different values of force was obtained.

1. Introduction

The cases of two-wheeler accidents are increasing day by day. The major affected parts of human body are spinal cord and head. The head protection device is available as helmet. To ensure the safety of spinal cord, the impact due to accident needs to be studied. The study here focusses on the lower two lumbar sections of human spine – L4 and L5.

1.1. Human Spine

The central nervous system includes spinal cord and brain. The spine processes and integrates the information. It is divided into five regions – cervical, thoracic, lumbar, sacrum and coccyx as seen in the figure 1. The table 1 shows the division of the five spinal cord regions into sub sections. The lumbar spine is composed of 5 vertebrae and the diameter increases on descending. The vertebra is divided into two portions – the anterior body and the posterior elements. The anterior body takes compressive loading of spinal cord. The posterior elements form a protective arch over the spine [1].
The functional spinal unit is connected by 10 ligaments. They restrict the motion of neutral structure by the motion resistance. Anterior longitudinal ligaments (ALL), Posterior longitudinal ligaments (PLL), Intertransverse ligaments (ITL), Ligamentum flavum (LF), Intertransverse ligaments (ITL), Interspinous ligaments (ISL), Supraspinous ligaments (SSL), Capsular ligaments (CL).

Discs are designed for two things; one is weight bearing and another is motion. High-water content is there within the disc and the combination of these all structures allow the disc to handle large compressive loads. It consists of two vertebrae, a disc, two facet joints and any other structures that span between these them.

1.2. Analysis tools used
The Software for the analysis is Hyperworks. Optistruct is used to study the impact of accident that comes upon the spinal cord and how much damage is caused. The Optistruct is used for analysis of linear and nonlinear problems under static and dynamic loadings.

1.3. Analysis method
First, the simplified model was taken for the analysis purpose. The tetrahedral mesh was made by taking the reference of surface mesh (2D auto mesh – edge deviation). The mesh was corrected and node to node connectivity was ensured. The axial compression force of 500 N was applied. The load applied is the average weight of the upper body that acts on the spine. Along with this the 7.5Nm moment was applied as a flexion. The disc was modelled as hyper elastic material and the bone as nonlinear material. The ligaments were made of 1D truss elements. The pre-processing was done and the results for the displacement, vonmises stress and strain are observed. It is observed that when the axial force was increased, all the values increased and the results matched with the literatures.

1.4. Literature reviewed
The literature is studied in different sections as given below on failure mechanics, loads acting on spinal cord and the analysis carried out.

1.4.1. Mechanics of failure of lumbar elements.
The lumbar vertebrae consist of cortical bone and cancellous bone. The cortical bone is denser, where the density of cancellous bone is comparatively less and the material is porous. The cortical shell surrounds the cancellous bone. The cancellous bone provides the strength and has a load carrying capacity that supports the lumbar vertebrae when subjected to impact [14]. The damage behaviour in the trabecular bone causes the loss of elasticity and the
permanent failure due to deformation [15]. This behaviour starts at yield point – point of failure of bone. When the load is applied beyond yield point, the disc structure can be damaged. The spine injuries happen due to disc failure. So, the disc needs to be analyzed to understand its behaviour. The nucleus is modelled as hyper-elastic material. The nucleus is surrounded by annulus fibers. In this analysis, the nucleus is modelled as solid and the annulus as 2D shell. When the test was done in tension, the endplate was failed than the disc itself [16]. Ligaments cannot take compressive load; they are only effective in compressive loading [17]. The load can be transferred by the ligaments without any deformation as they contain elastin fibers in them due to this, the ligaments are given elastic type properties in the analysis [18].

1.4.2.  Classification of the loads acting on spinal cord. The spinal loads are divided into two parts:

- Physiologic
- Traumatic

Physiological loads are loads due to normal activity of spinal cord and are again classified as short term loads, long term loads, repeated loads and dynamic loads. Traumatic loads occur suddenly and due to some impact. They generally have a great amplitude. This overload caused due to traumatic overloads can result into damage of disc and facet joints. When the load is applied to such a level, that the load bearing capacity is exceeded, there is short term loads acting at high level and this results into the structural damage [4].

1.4.3. Nonlinear static analysis. D. et. al. [10] used Finite Element Method for the spine analysis that includes the vertebrae, disc, muscles and ligaments. For the study of new type of lumbar spine’s artificial disc, CAD program and validation of experiment was carried out along with finite element method. Stress analysis was done for the FE model and new design. T. brown et al. [11] carried out analysis on the disc to understand its behavior. Various tests on mechanical strength and elastic properties were done. The main purpose behind this study was to obtain data on the physical properties of the disc and its related components. K. Uno et al. [12] carried out the non-linear analysis of the disc by modelling the disc behavior as spring type. The portion of lumbar spine used for analysis was L4-L5. Axial compression load, bending moment and torsion was applied and the study was carried out. The model was simplified to avoid the complexity in meshing that is the most important part in analysis. V. Goel et al. [13] performed nonlinear analysis on L4-L5 and L3-L5 segment of 3D model of lumbar spine. The behavior of spine was studying for various loading conditions that considers axial compression, lateral bending, flexion and extension. V. Goel et al. [14]. This paper is about the analysis of L3-L4 lumbar spine section. Axial compression force was varied from 200N to 2000N and the models were analyzed. The model was prepared in the form of laminar shells. The interlaminar shear stresses, disc bulge and displacement were the output results. S. et al. [15] The 42-fresh lumbar cadaver were modelled in axial compression and shear in anterior, posterior and lateral direction. The results were obtained in scatter in bending, torsion, flexion and axial compression. The try was made to reduce this scatter. For those eight different measures of disc were considered and the conclusion was drawn. A. Tsouknidas et al. [16] had done the dynamic study of the spine considering the anisotropic material of bone and ligaments were taken as solid properties. The study was aimed at reinforced segment of spine. The stresses encountered in the results were less critical and that concluded that the condition was osteoporosis. C. Wong et al. [17] carried out FEA of lumbar vertebrae and disc model. The trabecular solid bone was surrounded by cortical shell. The incompressible nucleus material of disc was surrounded by fibers that were made of nonlinear material. the mesh used was tetrahedral elements. The displacement-load curve used here in the paper was used as a comparison for the present report study. Z. & W et al. [18] carried out nonlinear analysis but considering the ligaments as solid elements rather than the truss elements that were used in the present report. The meshing was done with 3D tetrahedral elements. The properties of ligaments were considered as hyper-elastic.
2. Materials and method

The spine geometry is divided into three parts: Vertebrae, disc and ligaments as shown in figure 2. The vertebrae are made of cortical shell and cancellous bone. The disc includes nucleus, annulus and endplate.

![Figure 2. Classification of lumbar spine](image)

2.1. Model construction

The model construction is the first step. The process involves mesh generation, element classification and definition of interaction among various components with each other. Geometry, loading conditions, mechanical properties and computational cost are taken care during the mesh generation. In the lumbar model L4 and L5, the vertebra is taken as deformable part. It includes cortical shell and cancellous bone and bony endplates. The cortical shell and endplates are made using the shell elements and has a 2D triangular mesh – 3 node elements. The cancellous bone is made by using 3D tetrahedral mesh – 4 node elements. The contact between the various components is given using the Boolean operation in solid edit panel under the geometry option. The construction can be seen in the figure 3.

![Figure 3. Components of Lumbar vertebrae – cancellous bone, cortical shell and endplate](image)

The disc includes nucleus and annulus region. The nucleus is made using 3D tetrahedral mesh and the annulus part is 2D shell meshed using triangular mesh as shown in figure 4. The ligaments in the
lumbar spine are modelled as 1D elements using PBEAM property. The ligaments include CL, SL, TL and IL as seen in the figure 5.

![Figure 4. Disc nucleus and disc annulus](image1)

![Figure 5. Ligaments](image2)

2.2. Material property

The material property of the components is taken from the various literatures. The vertebrae are modelled as non-linear material (card image - MAT) and disc nucleus as hyper-elastic material (card image - MATHE). When the traumatic load is applied beyond the yield strain, the bone has the permanent deformation. So, the elastic plastic type material model is selected to avoid the complexity of anisotropic material as there is single loading. The yield stress and ultimate stress are taken for bone and the values are added in the form of table and the MATS1 is selected to add its properties in plastic range. Hyper-elastic material is taken for the disc nucleus and elastic material for the annulus. The material property of bone – cancellous bone and cortical shell are shown in table 2 and table3 respectively. Similarly, properties of disc nucleus and disc annulus are shown in table 4 and table 5.

| Table 2. Properties of cancellous bone | Table 3. Properties of cortical shell |
|---------------------------------------|--------------------------------------|
| **Material property** | **Value** | **Material property** | **Value** |
| Material card | MAT 1 | Material card | MAT 1 |
| E | 100 MPa | E | 12000 MPa |
| Nu | 0.2 | Nu | 0.3 |
| Ultimate tensile strength | 15.4 MPa | Ultimate tensile strength | 135 MPa |
| Yield strength | 13.3 MPa | Yield strength | 71.56 MPa |
| Type | plastic | Type | plastic |
| Property type | PSOLID | Property type | PSHELL |
Table 4. Properties of disc nucleus

| Material property | Value     |
|-------------------|-----------|
| Material card     | MATHE 1   |
| Model             | ODGEN     |
| Mu1               | 0.665     |
| Alpha1            | 2         |
| Mu2               | 2.73      |
| Alpha2            | -1        |
| Mu3               | -0.517    |
| Alpha3            | -3        |
| Property type     | PSOLID    |

Table 5. Properties of disc annulus

| Material property | Value     |
|-------------------|-----------|
| Material card     | MAT 1     |
| Youngs modulus    | 4.2 MPa   |
| Nu                | 0.45      |
| Type              | elastic   |
| Property type     | PSHELL    |

2.3. Nonlinear static analysis

To ensure that the meshing is done properly, node to node connectivity needs to be defined. The model was first meshed by auto mesh 2D, using edge deviation method to give the limits for minimum and maximum element size from 0.2 to 2 mm respectively. 3D mesh was created using this mesh as reference by Tetra mesh option. Various cleanup tools were used for improving the quality of mesh. The interference and penetration need to be checked and also the equivalence by removing any free edges if found. The figure 6 represents the final mesh of the model. Ligaments have 1D mesh, generated by using rigid option in Opti struct. The various materials and properties made needs to be assigned to the respective components.

The axial load of 500N is applied at the rigid node in the middle section of L4 vertebrae. This helps to distribute the force evenly to the entire part of the L4 vertebrae. The load of applied is the average weight of the upper human body acting on the spinal cord. The moment of 7500 N magnitude is applied in XY direction. The L5 section is constrained in all direction as seen in figure 7. The contact needs to be defined so that every load is transferred properly. The load collector with the card image of CONTSURF was created for L4, disc and L5. Here the entire solid surface is selected and given the contact as seen in figure 8. After making the contact surfaces, the contact needs to be created between them. This was done by making two contact cards, one for L4 – disc and another for Disc – L5, by using the load collector named as CONTACT. Various load collectors like NLPARM, NLADPT, NLOUT, CNTSTB were given. The load step is created, selecting the analysis type as nonlinear static and adding various cards – NLADAPT, NLPARM, NLOUT and CNTSTB. Various control cards are selected to get required output for the analysis like global output request.
3. Result and discussion

The postprocessing can be performed in HyperView. The .h3d file is loaded. Load factor can be varied to view the results at that particular load value. The initial value of deformation or stress at load factor 0 is 0. Final results can be obtained at the load factor = 1. For nonlinear analysis, 500 N axial compressive load and moment of 7.5kN were applied. Results obtained includes - displacement, element stresses (2D and 1D), element strains (2D and 1D). Analysis was conducted for three different axial compression force – 500N, 1000N and 1600N with the same applied moment. The contour plots are taken at 500N force and 7.5kN moment.

The contour plot for the element stresses – vonmises is shown in Figure 9. The maximum value is 25.2Mpa. As the disc behavior is the type of spring, that allows the maximum movement of spinal cord, the maximum effect of the force is found in the disc region. The contour plot for the element strain – vonmises is shown in Figure 10. The maximum value is 0.08096. The maximum value belongs to the disc region. The contour plot for the displacement – magnitude, is shown in Figure 11. The maximum value is 0.2481mm. As the force and moment are applied on the upper vertebrae, maximum deformation is observed in the same part. The contour plot for the element stresses 1D – axial, is shown in Figure 12. The maximum value is 0.2136 MPa for one side due to tension and 1MPa on other side due to compression. This range is due to moment application. As the ligaments are modelled as 1D elements, their behavior can be observed in 1D stresses type. The contour plot for the element strain 1D – axial, is shown in Figure 13. The maximum value is 0.2136 MPa for one side due to tension and 1MPa on other side due to compression. This range is due to moment application. As the ligaments are modelled as 1D elements, their behavior can be observed in 1D strain type.
The truss elements and the disc were of hyper elastic material and bone of non-linear material. The maximum stress and strain were found in the region of disc as due to the inner nucleus and its material properties. The displacement was maximum in the L4 region. All these above values calculated for 500N force increases for 1000N and 1600N force. The results for the values of force at 500N, 1000N and 1600N is shown in table 6. The displacement vs force graph is plotted as shown in Figure 14. The orange-colored curve is the result of analysis carried out and yellow-colored curve is the result taken from the literature [13]. Both the lines are parallel with slight deviation.
Table 6. Result table for the values of force at 500 N, 1000N and 1600 N.

| Result type          | 500N  | 1000 N | 1600N  |
|----------------------|-------|--------|--------|
| Displacement         | 0.248 | 0.51   | 0.845  |
| Element Stress 2D    | 25.2  | 50.79  | 82.04  |
| Element Strain 2D    | 0.081 | 0.1639 | 0.266  |
| Element Stress 1D    | 0.2136, -1 | 0.443, -2 | 0.7529, -3.16 |
| Element strain 1D    | 0.001424, -0.00669 | 0.002956, -0.01327 | 0.005019, -0.021 |

Some minor difference in the results from the literature is observed due to following factors:
1. Model was simplified for the analysis purpose.
2. Type of mesh used. Here tetra mesh was generated from 2d mesh reference. But in some papers hex mesh was also used. Results can differ due to the type of mesh used.
3. The ligaments were taken of same materials and the truss was taken in place of original component. The property of PBEAM was taken with circular cross section. In literature, the ligaments were modeled with PSOLID property.

4. Conclusion
The FEA of lumbar vertebra section was carried out and the results have been evaluated. The main focus was to study the behavior of lumbar spine, when the impact is more. The lumbar was the main effected area of the spine that needs to be protected. Results of the nonlinear analysis is matched with the literature [13] with some deviation. The reasons for the deviation are simplified geometry than CT data, meshing and ligaments modelled as truss elements.

Acknowledgements
The author would like to thank Mr. Veeshal Suthar from Design Tech System Ltd., Mumbai for his kind support and valuable guidance in finite element analysis.

References
[1] Michael Core (2015), The anatomy and function of spine
[2] Lumbar spine anatomy, cheerogeek.com
[3] Aiimsnets, Biomechanics of spine, Neurosurgery Education
[4] Spine Biomechanics, cnx.org
[5] Dietrich, M., Kedzior, K., Borkowski, P., Krzesiński, G., Skalski, K., & Zagrajek, T. (2005). A nonlinear analysis of the human vertebral column and medical recommendations that follow. Bulletin of The Polish Academy of Sciences-technical Sciences, 53, 179-194.
[6] BROWN T, HANSEN RJ, YORRA AJ. Some mechanical tests on the lumbosacral spine with particular reference to the intervertebral discs; a preliminary report. J Bone Joint Surg Am. 1957 Oct;39-A(5):1135-64. PMID: 13475413.
[7] Ueno K, Liu YK. A three-dimensional nonlinear finite element model of lumbar intervertebral joint in torsion. J Biomech Eng. 1987 Aug;109(3):200-9. doi: 10.1115/1.3138670. PMID: 3657107.
[8] Goel VK, Kim YE, Lim TH, Weinstein IN. An analytical investigation of the mechanics of spinal instrumentation. Spine (Phila Pa 1976). 1988 Sep;13(9):1003-11. doi: 10.1097/00007632-198809000-00007. PMID: 3061028.
[9] Goel VK, Monroe BT, Gilbertson LG, Brinckmann P. Interlaminar shear stresses and laminae separation in a disc. Finite element analysis of the L3-L4 motion segment subjected to axial compressive loads. Spine (Phila Pa 1976). 1995 Mar 15;20(6):689-98. PMID: 7604345.
[10] Smith, C. W. (January 1, 1979). "Discussion: “Fatigue Crack Growth Model for Part-Through Flaws in Plates and Pipes” (Nair, P. K., 1979, ASME J. Eng. Mater. Technol., 101, pp. 53–58)." ASME. J. Eng. Mater. Technol. January 1979: 101(1): 58.
[11] Alexander Tsouknidas, Savvas Savvakis, Yiannis Asaniotis, Kleovoulos Anagnostidis, Antonios
Lontos, Nikolaos Michailidis, The effect of kyphoplasty parameters on the dynamic load transfer within the lumbar spine considering the response of a bio-realistic spine segment, Clinical Biomechanics, Volume 28, Issues 9–10, 2013.

[12] C. Wong, P. M. Gehrchen, T. Darvann and T. Kiaer, "Nonlinear finite-element analysis and biomechanical evaluation of the lumbar spine," in IEEE Transactions on Medical Imaging, vol. 22, no. 6, pp. 742-746, June 2003, doi: 10.1109/TMI.2003.814783.

[13] iao, Zhitao & Wang, Liya & Gong, He & Zhu, Dong & Zhang, Xizheng. (2011). A non-linear finite element model of human L4-L5 lumbar spinal segment with three-dimensional solid element ligaments. Theoretical and Applied Mechanics Letters. 1. 10.1063/2.1106401.

[14] White, A.A., and Panjabi, M.M., 1990. Clinical Biomechanics of the Spine. 2nd Ed. J.B. Lippincott Co., Philadelphia.

[15] Yeh, O.C., and Keaveny, T.M., 2001. Relative Roles of Microdamage and Microfracture in the Mechanical Behaviour of Trabecular Bone. Journal of Orthopaedic Research 19, 1001 – 1007.

[16] Green, T.P., Adams, M.A., and Dolan, P. 1993. Tensile Properties of the Annulus Fibrosus: I. Ultimate Tensile Strength and Fatigue Life. European Spine Journal 2, 209 - 214.

[17] Yoganandan, N., Kumaresan, S., and Pintar, FA., 2001. Biomechanics of the Cervical Spine Part 2: Cervical Spine Soft Tissue Responses and Biomechanical Modelling, Clinical Biomechanics 16, 1 – 27.

[18] Shim, V.P.W., Liu, J.F., and Lee, V.S., 2006. A Technique for Dynamic Tensile Testing of Human Cervical Spine Ligaments. Experimental Mechanics 46, 77 – 89.