

DEVELOPMENT OF L1 TO L5 FINITE ELEMENT MODEL OF LUMBAR SPINE: A BIOMECHANICAL STUDY

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Abstract: A finite element method has contributed more in the field of biomechanics by providing prominent solution methods for understanding functional biomechanics of lumbar spine. So far, eight well-established finite element (FE) models of the lumbar spine (L1-L5) of different research centres around the globe were subjected to pure and combined loading modes and compared to *in vitro* and *in vivo* measurements for inter vertebral rotations, disc pressures and facet joint forces. To develop a surface model of L1 - L5 from CT scan has more complications and it is very difficult to extract, even though the CT model will be patient specific condition. Availability of CT scan data is also rare because of ethical concern. The purpose of the present work is to develop a new standard validated model from L1 -L5 by measured geometrical data available from reported literature. The validation was done comparing with literature results for 10 Nm moment to predict the range of motion.

Keywords: FEA, Biomechanics, Mesh sensitivity, Lumbar vertebrae, Range of motion.

1. Introduction

The Lumbar spine provides flexibility to the body supports the body weight and protect nervous structures. Low back pain is a frequently found disorder in a high percentage of the world population. Clinically relevant and accurate modelling of complex biological systems such as the human lumbar spine remains challenging, yet promising, with the potential to substantially enhance the quality of patient care. Due to its ability to represent complicated systems with nonlinearities by material, loading in irregular manner and geometrical domains, finite element (FE) method has been identified to be an important computational tool in various biomedical fields and has been utilised widely for representing spinal biomechanics. In comparison to *in vitro* or *in vivo* studies, computational methods are advantageous in offering powerful response solutions while at the same time effectively dealing with the ethical concerns related to the use of

live animals in experiments. Moreover, use of computational models may greatly diminish the need for experimental investigations that utilize post mortem human and animal specimens.

Xu et al. [1] studies about the inter-subject variability of geometries and material properties in human lumbar spines. By this improved prediction, five FE models (L1-L5 spinal levels) of the human lumbar spine were developed based on five healthy living subjects with identical modelling method. The five models were extensively validated through experimental and computational results in the literature. Mesh convergence and material sensitivity analysis were also conducted. Nicola Cappetti et al. [2] proposed the realization of a parametric/ vibrational CAD model of a normotype lumbar vertebra, which could be used for improving the effectiveness of actual imaging techniques in informational augmentation of the orthopaedic and traumatological diagnosis. In addition, it could be used for ergonomic static and dynamical analysis of the lumbar region and vertebral column. FE Studies were reported in the lumbar spine for spondylolisthesis [3], ligament transection [4], herniated disc [5], muscle dysfunction [6] and movement of spine segments in all physiological motions [7-13]. Frank Niemeyer. [14] Studied the impact of geometrical variability in spines geometry which strongly affects range of motion. Dreischarf et al. [15] compared the range of motion, intradiscal pressure, and facet joint contact forces of eight well-established finite element (FE) models of the lumbar spine (L1-L5) of different research centres around the globe. A finite element study also has been made based on the variation in geometrical parameters which in turn affects different disc properties.

By understanding all the research work published so far, the present work focuses on developing a FE model for L1-L5 Lumbar region. This model is developed by taking the measurements from literature instead of acquiring surfaces from CT images so that a general intact model can be generated which is suitable for many future researches. The model is validated using experimental results by applying the same

loading and boundary condition as done in experimental method.

2. Materials and Methods

2.1 Cad Modeling

A 3D CAD model was developed based on the dimensions extracted from literature [16] and is been compared with the CT image extracted for posterior regions. The CAD model generated is shown in the Figure 1.

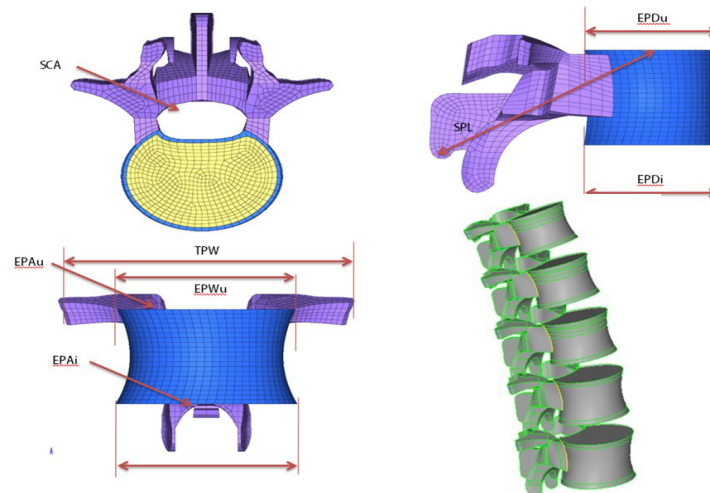


Figure 1. Surface Model of L1 - L5 Lumbar segments

2.2 Mesh Sensitivity Study

Mesh sensitivity study was conducted to fix the size and shape of the element which can be used for developing the finite element model. Two different element shapes were considered, (a) Hexahedral element and (b) Tetrahedral element with three different element sizes as tabulated (Table 1.), by

considering both first order and second order element. For performing the mesh sensitivity study the anterior body of L3-L4 is only considered without considering the vertebral arch. From reviewing the results of mesh sensitivity study hexagonal element of size 1.5 is chosen for creating the FE model. Mesh sensitivity study is done under pure compression condition of load 150N as shown in Figure 2.

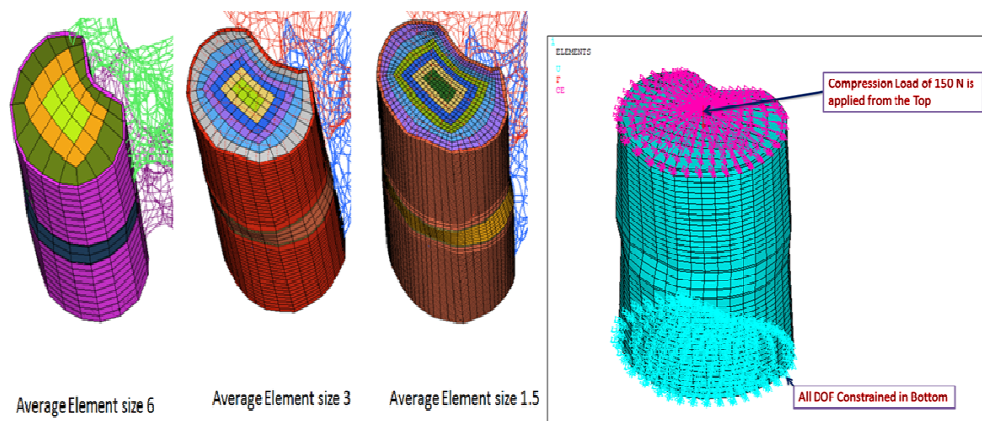


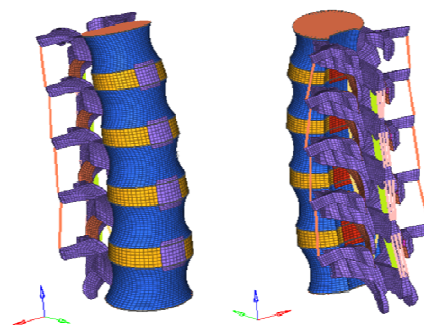
Figure 2. Anterior region of L3 -L4 segment with Hexahedral mesh

Table 1. Comparison of mesh sensitivity analysis using different elements

S. No.	Type	No. of nodes	No. of elements	Maximum stress (MPa)	Maximum displacement (mm)
1	Hex-first order EL 6	1703	1366	3.68	0.224
2	Hex-first order EL 3	9535	8366	4.01	0.225
3	Hex-first order EL 1.5	62614	58242	4.46	0.226
4	Hex-second order EL 6	6436	1366	4.56	0.225
5	Hex-second order EL 3	36902	8366	4.98	0.226
6	Hex-second order EL 1.5	245954	58242	5.02	0.227
7	Tetra-first order EL 6	1729	8317	3.01	0.185
8	Tetra-first order EL 3	9644	50745	3.49	0.183
9	Tetra-first order EL 1.5	63257	352683	3.16	0.204
10	Tetra-second order EL 6	12379	8317	4.16	0.224
11	Tetra-second order EL 3	72241	50745	4.56	0.225
12	Tetra-second order EL 1.5	487689	352683	5.02	0.225

2.3 Finite Element Model

Based on the element size and shape chosen from mesh sensitivity study a finite element model is developed from L1 - L5 segments (Figure 3). Since the second order element will have more number of nodes which in turn increases the calculation time, First order element of size 1.5 mm is chosen to generate the FE model. The ligaments are represented using both shell elements and link elements to avoid element distortion error. The FE model is checked for ideal element quality. The FE model is generated using hexahedral element of average element size 1.5 mm by considering the realistic model of lumbar spine.

**Figure 3.** Meshed model of L1-L5 Lumbar regions with ligaments

2.4 Material Properties And Boundary Conditions

The material properties applied for different layers of bone are referred from literature and it is tabulated (Table 2). The layers of bones are explained in Figure 4. Vertebrae is modelled using solid element

(Hexahedral Element) and the ligaments are modelled using shell element and Link element to avoid element distortion while performing numerical simulation. The element type used to model solid element Solid 185, Shell element Shell 181 and Link element Link 180.

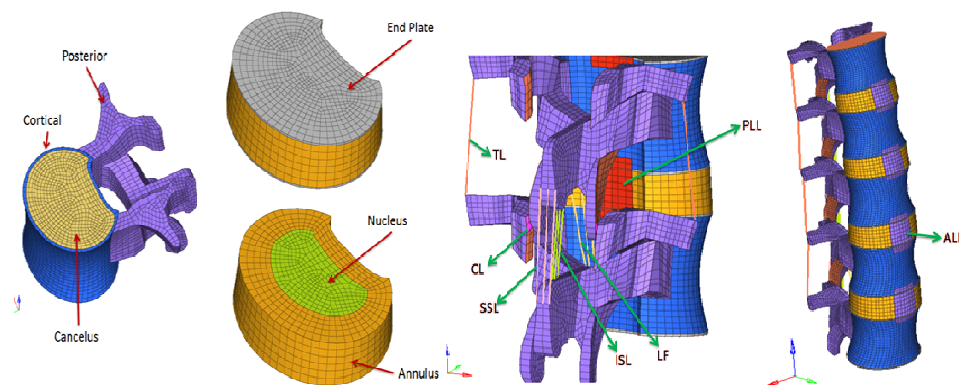


Figure 4. Components of the lumbar segments

Table 2. Material Properties used for lumbar segments

Components	Young's modulus (MPa)	Poisson's ratio	Cross section area (mm ²)
Cortical	12000	0.3	-
Cancellous	100	0.2	-
Endplate	24	0.4	-
Annulus	8.4	0.45	-
Nucleus	1	0.499	-
ALL	20	-	-
PLL	20	-	-
TL	58.7	-	3.6
LF	19.5	-	40
ISL	11.6	-	40
SSL	15	-	30
CL	32.9	-	-

3. Results and Discussions

The standard model was developed by referring the dimensions extracted from the literature. After generating the CAD model, for performing the numerical simulation a FE model need to be developed. For identifying the ideal element type and element shape a mesh sensitivity check has been performed. Based on the results of the mesh sensitivity study

results, element size of 1.5 mm and hexahedral shape is chosen for generating the FE model of L1- L5 lumbar spine region. Initially, FE model for L3-L4 vertebrae along with disc region is developed and a pure compression test is performed to review the movement of facet region. Based on the facet movement the shape facet has been adjusted to obtain better results.

The FE model generated is analysed for flexion, extension, axial rotation (both directions) and lateral

bending (both directions), as shown in Figure 5. The results compared with the literature are the range of motion of each vertebral body for validation purpose. There are different other parameters can be extracted but the range of motion is used for ideal validation purpose. The stress and displacement values are

captured from the numerical simulation performed for the boundary conditions and shown in (Figure 6.). The range motion can observed from the displacement happened in each vertebral level and the maximum rotation happened in the particular vertebrae.

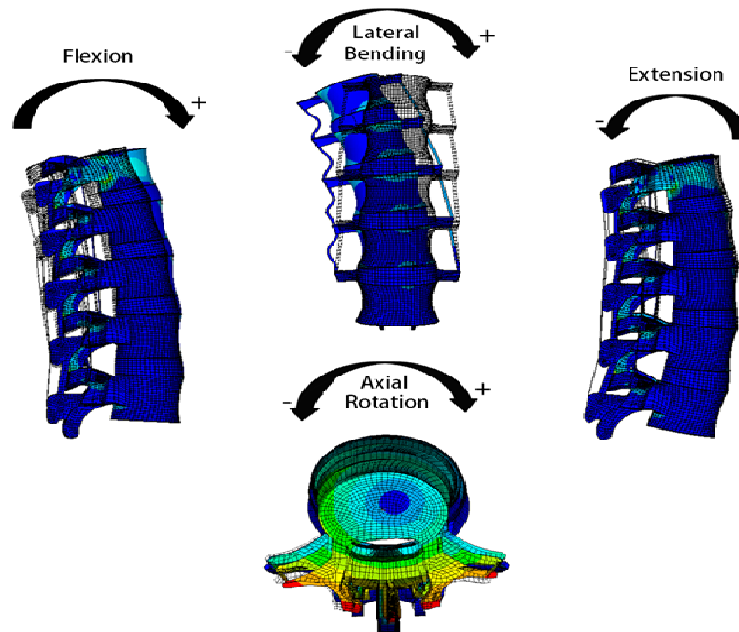


Figure 5. Simulating the all physiological motions

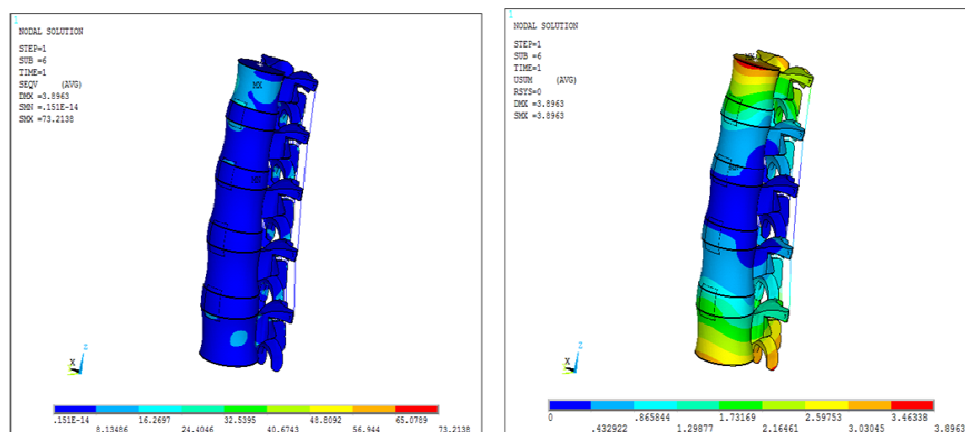


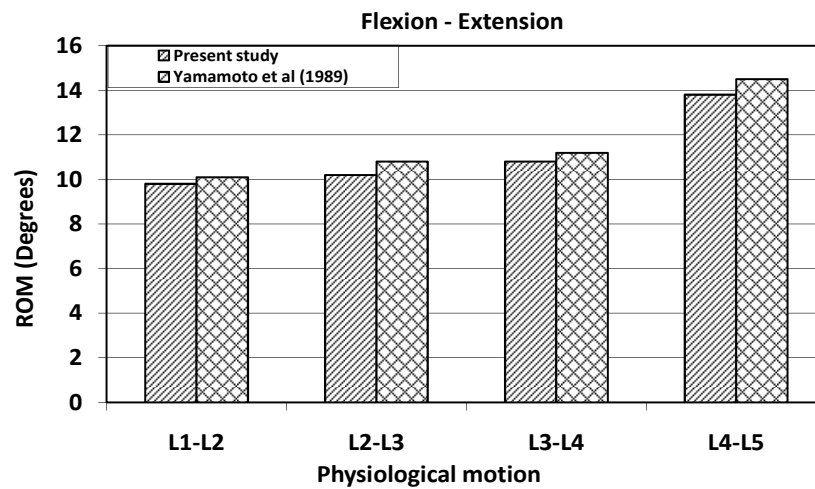
Figure 6. Stress distribution and Displacement from L1-L5 segments for flexion movement

These results indicate a maximum variation of 5.5% in flexion-extension, 9.5% in axial rotation and

8.75% in lateral bending were observed as compare to literature [19]. These results are tabulated table 3-5.

Table 3. Range of motion for flexion and extension

Level	Flexion – Extension (Degrees)		
	Yamamoto et al. (1989)	Present study	Percentage difference
L1-L2	10.1	9.8	2.9%
L2-L3	10.8	10.2	5.5%
L3-L4	11.2	10.8	3.5%
L4-L5	14.5	13.8	4.8%

**Figure 7.** Comparing the range of motion of flexion and extension with *in vitro* study.**Table 4.** Range of motion for axial rotation

Level	Axial rotation (Degrees)		
	Yamamoto et al. (1989)	Present study	Percentage difference
L1-L2	2.1	1.9	9.5%
L2-L3	2.6	2.4	7.69%
L3-L4	2.6	2.5	3.85%
L4-L5	2.2	2.0	9.09%

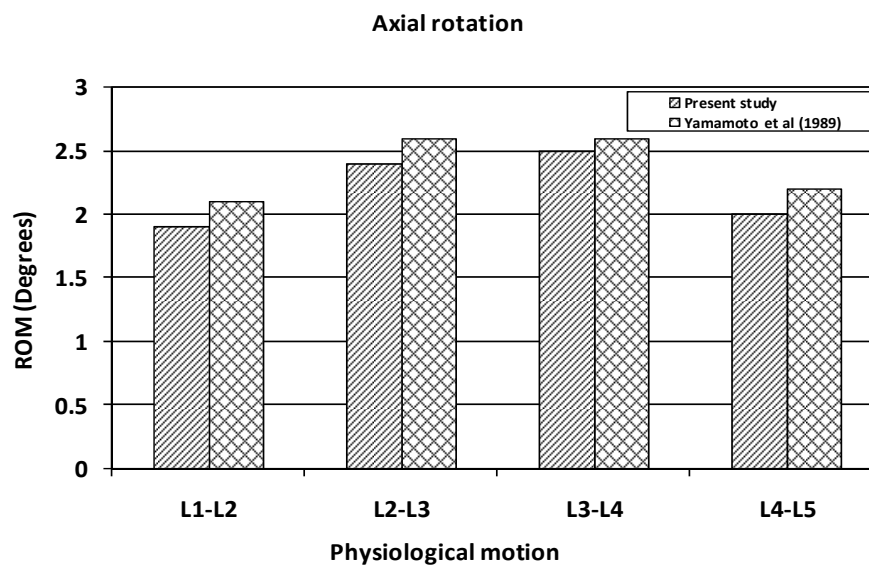


Figure 8. Comparing the range of motion for axial rotation with *in vitro* study.

Table 5. Range of motion for lateral bending

Level	Lateral bending (Degrees)		
	Yamamoto et al. (1989)	Present study	Percentage difference
L1-L2	4.9	4.5	8.16%
L2-L3	7.0	6.4	8.57%
L3-L4	5.7	5.17	9.3%
L4-L5	5.7	5.35	6.14%

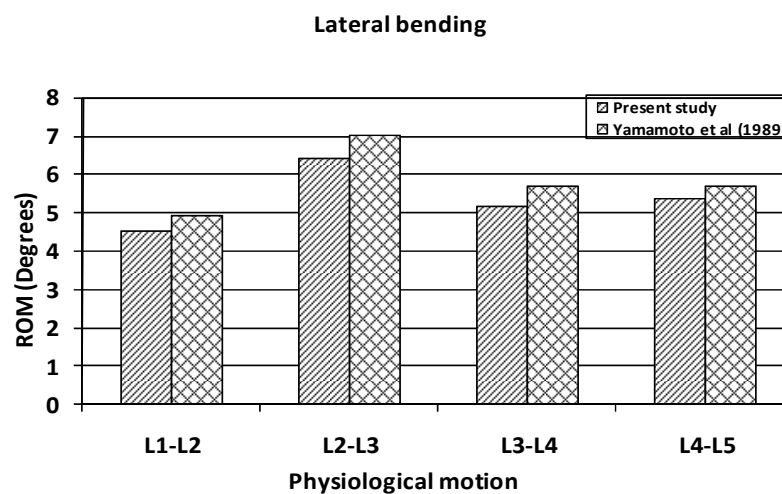


Figure 9. Comparing the range of motion for lateral bending with *in vitro* study.

4. Conclusion

The standard model was developed by referring the dimensions extracted from the literature and it is used to produce the FE model. The FE model generated is analysed for all physiological motion with a load of 10 Nm moment applied in respective directions. The range of motion results of each vertebral body is compared with the literature for validation purpose. There are different other parameters can be extracted but the range of motion is used for ideal validation purpose. By observing the results of different physiological motion, the flexion - extension results vary by a maximum of 5.5%, the lateral bending results vary by a maximum of 8.57% and the axial rotation results vary by a maximum of 9.5%. These values are having a difference in maximum of 9.5 percentage, because of the facet shape, this can be even improved altering the facet shape and position likewise we can reduce the percentage of change. This validated model can be used for any future study in disc degeneration, vertebral compression fracture and any other pathological disease. Since it is a standard model developed from dimensions arrived from several specimens, this model can be modified and used for further studies.

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