

3D Parametric Model of Whole Lower Cervical Spine (C3-C7)

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Abstract: The purpose of this study is to create a 3D parametric model of lower cervical spine and to validate it by examining the model with finite element method. First step was creating a master model with capability of simple changing of the parameters which could be extracted from CT-scan images. By implementation of these parameters on the model, it would be updated for each case. Next step was mesh-generating of the model. Then the material properties for each part of the model have been implemented. In this model vertebra, endplate, facet have been considered as simple elastic solids, nucleus, annulus and ligaments have been considered as an incompressible solid, hyperelastic solid, non-linear springs respectively. After finalizing the modeling procedure, analyzing of the model for each case would be completed. The results have been compared with some references and after validation of the model; it could be used for extended studies.

Key-Words: Biomechanics, Finite Element, Spine, Hyperelastic, Parametric, Modeling, Cervical

1 Introduction

One of the most popular methods of studying about spine and its reaction to different loads is finite element method. The advantages of this method are clear: possibility of modeling complex geometries and boundary conditions, possibility of non-linear material and geometry simulation, parametric studies, fast, good visualization, reliable results and many others. Although an exact model would be more reliable and performable, a parametric model with sufficient accuracy would be more practical for regular studies. In order to reduce the complexity of the model, a parametric model was used. For this purpose, first appropriate parameters have been identified then a geometrical model with appropriate mesh would be generated. Suitable mechanical properties appropriate boundary conditions and loads have been added to the model. After analysis, the results would be compared to some related references to validate the model. The validated model would be ready and reliable for extensive studies.

2 Method

The modeling procedure was done as follows:

2.1 Geometric Modeling

First some consumption which has been considered to simplify the model will clarify.

- 1- Considering cervical spine symmetric with respect to sagittal plane.
- 2- All vertebrae C3 to C7, considered having similar geometries and parameters with different values.

2.1.1 Parameter Selection

The most critical step of the modeling was selecting the optimum parameters to define each vertebra. By studying similar studies and previous parametric models which have been issued in some references [2, 7, and 13] and studying the geometry of the vertebra through CT-Scan images, finally 30 parameters have been selected to verify each vertebra. Two parameters for each motion segment have been chosen to identify the relative position of vertebrae to each other. Two parameters for thickness of endplate of each vertebra and gap between facets for each segment have been considered. The last considered parameter was the surface area ratio of nucleus to whole inter-vertebra disk area for each segment. List of necessary parameters for whole model is presented in table 1.

Parameters	Qty
Vertebra	$5 \times 30 = 150$
Assembling	$4 \times 2 = 8$
Endplates	$4 \times 1 = 4$
Facets Gap	$4 \times 1 = 4$
Nucleus surf. Ratio	$4 \times 1 = 4$
Total	170

Table1. Overview of whole model No. of parameters

2.1.2 Vertebra Master Model

After selecting the suitable parameters for defining the vertebra, based on the prepared draft of the model, a master model of a vertebra have been created in the modeling software with parametric modeling capability. Then on upper surface and lower surface of vertebra body, end plates have been modeled with parametric height (Figure 1).

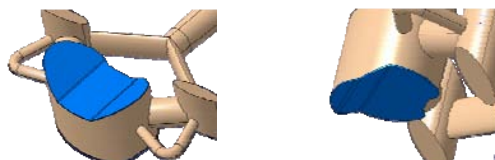


Figure1. A vertebra master model with related endplates

2.1.3 Assembling the vertebrae

When the master model of vertebrae has been created, they should be assembled to prepare the lower cervical spine column. For assembling the column, one parameter is required for distance between two opposite surface of vertebrae and one parameter for the angle between those surfaces for each motion segment. These parameters can easily be measured through X-ray or CT-Scan images. By considering these parameters, the master model of vertebra column would be assembled. Required parameters for assembling the lower cervical column are shown in figure 2.

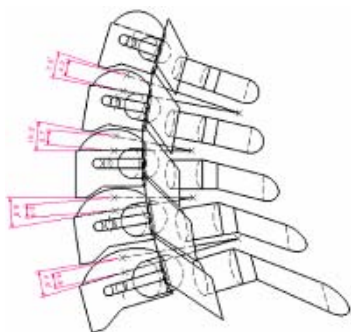


Figure2. Required parameters for assembling the column

2.1.4 Modeling the soft tissue

After modeling the bony structure, it is turn of modeling the soft tissues. It is consisted of inter-vertebra disks, facets and ligaments. To model inter-vertebra disk, the volume between two neighbor vertebra bodies would be filled. The volume would be divided into two parts. Inner part (nucleus) would be ellipse-shaped volume with a surface area ratio (about 50%) to the whole disk surface area. The rest of the volume would be considered as annulus. Figure 3 shows the modeled nucleus and annulus.

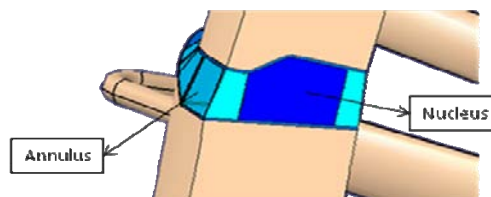


Figure3. Modeled Nucleus and Annulus

To model the facets, the mid-plane between sitting surfaces of opposite facets would be considered. The volume between sitting surface of each facet and this mid-plane would be filled with facet. A gap would be considered on both sides of the mid-plane with parametric width. Modeled facets are shown in figure 4.

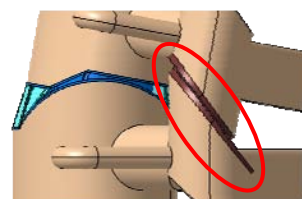
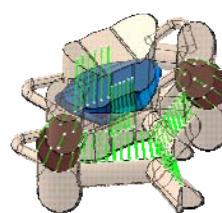


Figure4. Facets (brown) and the gap between facets

Five ligaments have been considered for this model, Anterior Longitudinal Ligament (ALL), Posterior Longitudinal Ligament (PLL), Flavam Ligament (FL), Capsular Ligament (CL) and Inter-spinous Ligament (ISL). To model each ligament, several parallel springs have been used to simulate the ligament. Figure 5 and table 2 shows the place and quantity of considered springs for each ligament.



Ligament	No. of springs
ALL	6
PLL	6
FL	20
CL	2*10=20
ISL	6

Figure5 and table2 Position and No. of ligaments

2.1.5 Mesh generation on the model

For finite element analysis, all geometric parts should have been meshed. All of the parts have been considered as first order solid tetrahedral mesh (although for such a complex geometries second order elements would be better, but for contact areas first order elements are preferred), except ligaments which have been considered as non-linear springs.

2.1.6 Material properties

For finite element modeling, proper material properties are very crucial factors and have

magnificent effect on the results. Considered properties for each part of the model are as follows:

- Vertebra: With considering the fact the vertebra is stiffer than other parts of the model, so in most of studies it is considered as a rigid body. In this study it is considered as a union solid body with material properties which are shown in table 3.
- Endplates: The material is presented in table 3.
- Inter-vertebra disk: It is consisted of two parts. Nucleus, an almost incompressible solid (see table 3) and Annulus, a hyperelastic material with behavior shown in figure 6.
- Facets: In this study, an empty gap has been considered between them. The facet surfaces have friction coefficient equal to ($\mu=0.01$).
- Ligaments: They have been considered as non-linear springs with no effect on compression (tension only) [7]. Table 4 presents the force-displacement values for each ligament.

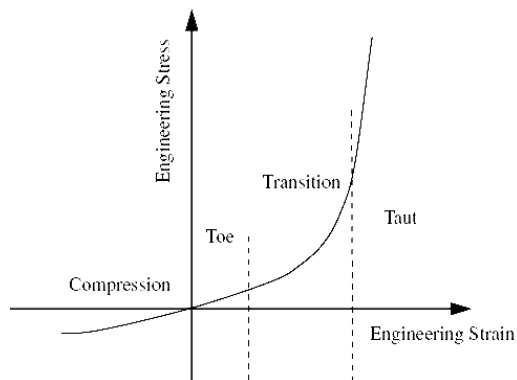


Figure6. Hyper-elastic behavior of annulus [12]

Item	E (MPa)	ν
Vertebra	12000	0.3
Endplate	500	0.3
Nucleus	3.5	0.499

Table3. Vertebra, endplate and nucleus material properties

ALL		PLL		LF		ISL		CL	
F	dl	F	dl	F	dl	F	dl	F	dl
0	0	0	0	0	0	0	0	0	0
5.5	1.2	4.5	1.2	1.5	1.8	1.5	1.3	1.5	3.6
10	2.5	8.5	2.2	3	3.5	2	2.8	2.6	5
13.5	3.7	11	3.2	3.5	5.1	4	4.1	4.3	7.5
16.5	4.8	13.5	4.3	5	6.9	5	5.5	5.2	9.5
19.5	6	15	5	5.5	8	5.5	7	5.4	9.9
54.5	20	47	20	11	20	9.8	20	10.5	20

Table4. Ligaments force-displacement behavior (F considered as N and dl as mm.) [7]

2.1.7 Extracting the parameters

To prepare the model of each case, mentioned parameters should be derived through CT-Scan images (a low resolution images would be enough). To achieve this goal, all required parameters have been measured from CT-Scan images through image processor software like Mimics. A sample of this process is shown in figure 7. All measured parameters are recorded in an excel file which is link to the model. After finalizing this step, the complete model will be updated automatically.

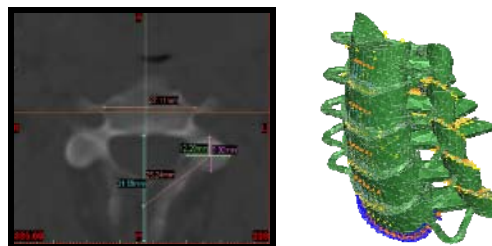


Figure7. Parameters measuring and updated model

2.2 Analyzing the model

When modeling finished, analyzing of the model have been started. In this study each motion segment and whole lower cervical spine will analyze under different loads. After applying boundary condition and standard loads the range of motion (ROM) of the model would be calculated and the results would be checked with some references (laboratory tests in-vivo or in-vitro and similar FEM studies). The model would be validated in two phases; at first motion segments, then the whole lower cervical spine. In first phase, model would be modified to reach the validity. When the final properties are convinced then the whole model would be validated.

2.2.1 Boundary condition and loads

For each analysis, the lower surface of vertebra body of the lowest vertebra would be considered as a fix part (zero degree of freedom). Such a boundary condition is not exactly the same as in-vivo condition, but it would be the same as in-vitro and other FEM tests. Standard loads which are applied to these models are varied but most of them are moments in the range of 0-3.0 N.m in directions of flexion, extension, lateral bending and axial torsion. A sample of boundary condition and loads are shown in figure 8.



Figure8. A sample of boundary condition and loads

2.2.3 Rotation angle calculation

When moments are applied to the model the rotation angle of upper vertebra would be calculated to indicate the range of motion under specific moment. To calculate the rotation angle, as loading and deforming is planar, the following formula can be used to calculate the rotation angle. For this purpose the coordinates of two specific points before and after deformation will be recorded.

$$\cos\theta = \frac{U \cdot U'}{|U| |U'|} \quad (1)$$

Where:

U, U': Vectors which connect two points from upper vertebra before and after deformation.

θ: Angle between U and U' which indicate the rotation angle of upper vertebra.

2.3 Results and validation

The main purpose of this study is analyzing the range of motion (ROM) of the model under different loads. As mentioned before, the result is derived for each motion segment and whole lower cervical spine. Figure 9 shows the direction and name of applied moments.

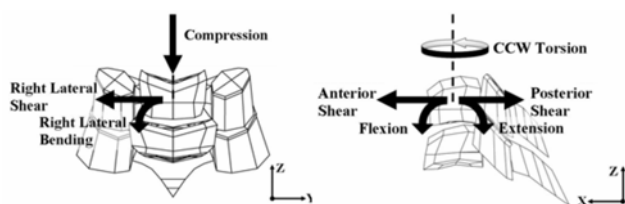


Figure9. Direction and name of different moments

2.3.1 Motion segments

Each motion segment has been analyzed under different moments between 0-1.5 N.m in directions of flexion and extension.

The result for ROM of each motion segment under different moments is shown in diagram 1.

It is obvious that ROM under extension moments are limited more than ROM under same flexion moment (before reaching the facets to each other,

the difference would mostly be the cause of ligaments, but when facets reach each other, facets will play the main role).

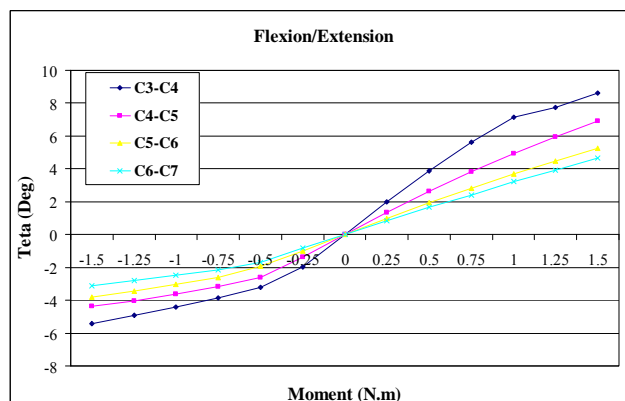
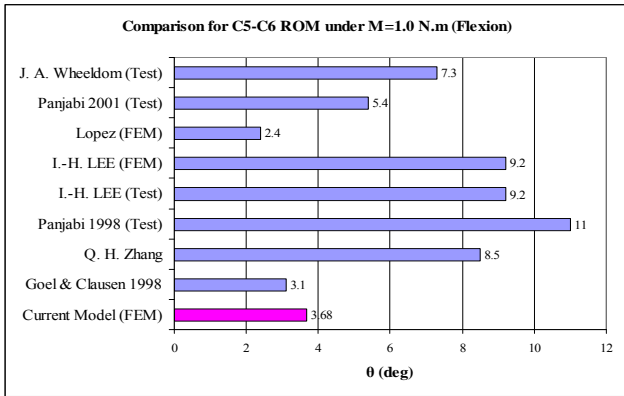


Diagram1. The comparison of ROM of different segments under flexion and extension moments

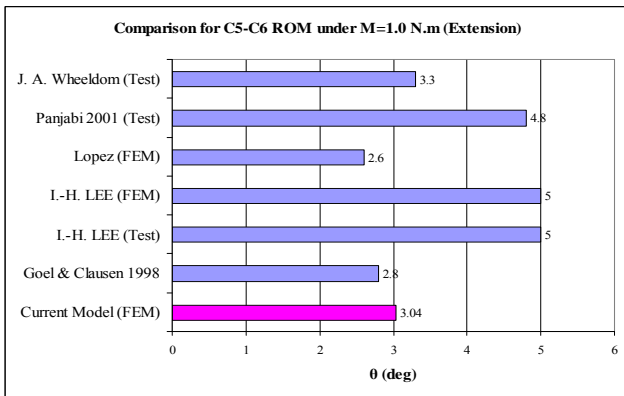
To validate the model, the above presented results should be compared to the acceptable FEM and laboratorial studies. Table 5 presents the comparison result of flexion/extension for each motion segment of current model under moment 1.0 N.m with some references. The comparison indicator is prepared for C5-C6 motion segment in diagram 2. As it could be seen, the model has an acceptable behavior for flexion and extension.

M=1.0 N.m					
Flexion					
	C3-C4	C4-C5	C5-C6	C6-C7	Ref.
Current Model (FEM)	7.2	4.9	3.7	3.2	
Goel & Clausen 1998	-	-	3.1	-	[4]
Q. H. Zhang	10	8.5	8.5	8	[6]
Panjabi 1998 (Test)	8.5	10.5	11	8.5	[10]
I.-H. LEE (Test)	6.4	-	9.2	-	[5]
I.-H. LEE (FEM)	7.6	-	9.2	-	[5]
Lopez (FEM)	3	3	2.4	1.8	[7]
Panjabi 2001 (Test)	4.2	5.2	5.4	3.6	[11]
J. A. Wheeldom (Test)	6.67	6	7.3	6	[3]
Extension					
Current Model (FEM)	4.4	3.6	3.0	2.5	
Goel & Clausen 1998	-	-	2.8	-	[4]
I.-H. LEE (Test)	4.2	-	5	-	[5]
I.-H. LEE (FEM)	4.2	-	5	-	[5]
Lopez (FEM)	2.6	2.2	2.6	3.6	[7]
Panjabi 2001 (Test)	3.8	5.2	4.8	3.6	[11]
J. A. Wheeldom (Test)	3.3	3	3.3	4.3	[3]

Table5. Comparison result of C5-C6 under moment 1.0 N.m (Flexion/Extension)



(a)



(b)

Diagram2. Comparison result of C5-C6 under moment 1.0 N.m, a) Flexion, b) Extension

2.3.2 Whole lower cervical spine

After validation of motion segments, now the ROM of whole cervical spine under different moments and directions are presented in diagram 3.

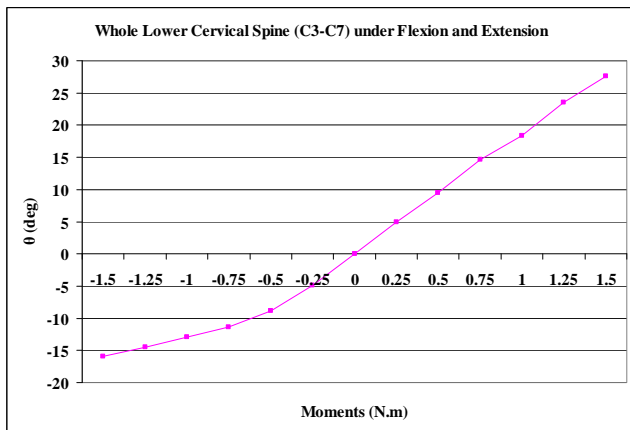


Diagram3. ROM of whole lower cervical spine

The comparison between some simulations (FEM) and laboratorial studies and current model is shown in table 6.

Load	ROM (deg)		
	Current ¹ (FEM)	Nicolella ² (FEM)	J. A. Wheeldom ³ (Test)
0.5 (Flex.)	9.5	17.1	21.3
1.0 (Flex.)	18.4	27.9	32
1.5 (Flex.)	27.6	35.4	14.5
0.5 (Exten.)	8.9	6.4	10.7
1.0 (Exten.)	13	10.7	17.3
1.5 (Exten.)	15.9	14.5	18.7

Table6. Comparison of ROM of whole model
¹-C3-C7, ²- C3-T1 [2], ³-C2-T1 [3]

More number of motion segments in presented references makes the judgment difficult. To make the results more suitable for comparison, the effect of extra segments should be calculated and removed. To calculate the portion of each motion segment in total rotation, the ROM of each segment will be divided to ROM of whole model. The average portion of each motion segment and weight factor is presented in table 7 (weight factor for C5-C6=1).

Segment	Por. Of rotation	Weight Factor
C3-C4	35%	1.67
C4-C5	27%	1.29
C5-C6	21%	1
C6-C7	17%	0.81

Table7. Portion of each segment in total ROM

If the effect of C2-C3 and C7-T1 has been considered as C3-C4 and C6-C7, so for ref. [2] and [3], the modifying factor would be equal to 0.85 and 0.64. The comparison of modified results is shown in diagram 4.

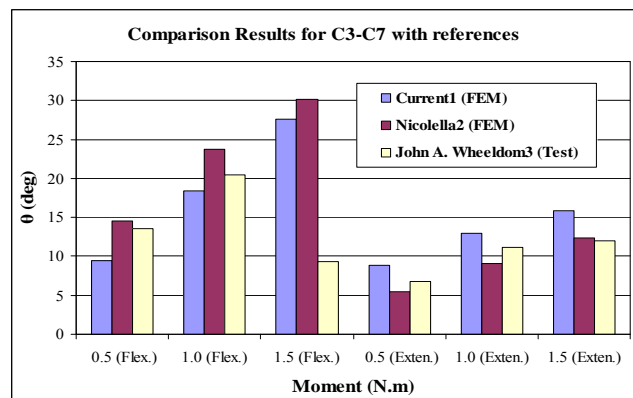


Diagram4. Comparison of modified values for complete model

As it could be seen, the results match with the references well, the remained difference could be as the result of the difference between test cases and some consumption. It shows that the model is validated for standard loads and it could be used for similar studies.

3 Discussion

Presented model is a parametric three dimensional model of lower cervical spine which is updated simply just by measuring the parameters from CT-Scan images and implementation of measured parameters to the input file (an excel file). This model validated through a two phase validation procedure, validation of each motion segment and validation of the whole model. When validation is finished and the results have been matched to reference, now the model has been validated and reliable to be used for similar FEM analysis.

There are several usages for this model:

- Analyzing the effect of age, size and other physical properties of different cases: by analyzing different models with different ages or size and investigate the effect of mentioned physical characteristics.
- Analyzing artificial disks and facets: by changing the considered artificial parts in the model and investigates the behavior of the artificial parts and checks the results.
- Spine deformity: by modeling different cases and analyzing them under different conditions (even with different material properties), then recording the parameters and related results. The prepared data base can be used as an input data base for a prepared neural network program to be trained and checked with provided data. The prepared neural network can be used as a powerful tool to predict the behavior of a new case with measured parameters under specific conditions.

Mentioned usages would be future studies of the spine group.

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