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Load Sharing in L4-L5 Spinal Motion Segment Using an Asymmetrical Finite Element Model

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Abstract - Lumbar spine degeneration diseases require precise prediction of biomechanical parameters. These parameters include stress in ligaments, intradiscal pressure and facet loads. For this purpose, several symmetrical FE models of lumbar spine have been proposed previously with inherent simplifications in design. Such models may not give realistic results for biomechanical analysis because of the assumptions in their design. An asymmetrical 3D finite element L1-L5 lumbar spine was developed using computed tomographic scans of a healthy individual. All lumbar spinal elements were added to the model, including vertebra, intervertebral discs, ligaments and facet joints. 400N pre-compression load was applied and model was simulated at 10Nm pure moment in all six planes of motion. L4-L5 motion segment was used for prediction of biomechanical parameters. Facet loads reached the maximum value of 200N in extension and axial rotation. Intradiscal pressure had highest value in lateral bending where it was predicted as 2.3MPa. Flexion showed significantly higher pressure of 1.67MPa in disc. Stress in interspinous ligament had maximum value of 3.27MPa in flexion motion whereas capsular ligament had maximum stress value of 29MPa in extension motion. Based on these predictions and literature values, it is concluded that facet joints and capsular ligaments are effective in load sharing during extension motion. Interspinous ligaments are utilized during flexion while intervertebral discs performed load sharing in lateral bending, axial rotation and flexion.

***Keywords*:** Finite element model, Facet loads, Intradiscal pressure, Ligament stress.

1. Introduction:

Finite element (FE) models have been seen as an alternative to *in vitro* testing for lumbar spine. These computational models are repeatable, flexible in parameter adjustment and cheap to develop and use (Goel et al., 1998). Moreover, these models can be utilized for the prediction of parameters that are physically difficult to perform *in vitro*. FE models are being employed in the study of effects of destabilization and interspinous process devices (ISP). Therefore, it is pertinent to predict load transfer ability of those lumbar components which are mostly affected in these two surgical scenarios.

A review of literature reveals that the most of currently used FE models have inherent simplifications (Lee et al., 2004; Kiapour et al., 2007; Erbulut et al., 2014). These models are symmetric along mid-sagittal plane whereas real human lumbar spine is asymmetrical. Some models assign material properties which are rigid than the real human spine. Keeping in view these drawbacks of previous models, we have proposed an asymmetrical lumbar FE model. The aim of current study is to investigate biomechanical properties of lumbar spine using proposed FE model.

2. Methods

2.1. Mesh Creation

A three dimensional finite element mesh (FEM) of lumbar spine (L1-L5) was developed using computed tomography (CT) scans of a healthy individual. The FE model was asymmetric across mid-sagittal plane. The development procedure was divided in three parts: 1) Image reconstruction; 2) Mesh creation; and 3) Material properties. Image reconstruction was performed on the CT scans using image processing software Mimics® Version 14.1 (Materialise, Inc., Leuven, Belgium). Intervertebral discs were manually developed because they were not visible in CT scans. Next step involved creation of hexahedral mesh on the vertebra and disc surfaces, which was performed in the IA-FEMESH software (University of Iowa, IA). The resulting STL files were exported to ABAQUS where all vertebras and discs were merged. Moreover, all seven ligaments were created using truss line elements. GAPUNI element was used for facet apophyseal joints. Material properties were assigned to each component of L3-L4 motion segment using values from literature (Erbulut et al., 2014). Table 1 summarizes these material properties.

Table 1.Material Properties of Lumbar FE Model Components.

Component	Element Formulation	Modulus (MPa)	Poisson's Ratio
Vertebral Cancellous Bone	Isotropic, elastic hex elements	450	0.25
Vertebral Cortical Bone	Isotropic, elastic hex elements	12000	0.3
Posterior Bone	Isotropic, elastic hex elements	3500	0.25
Nucleus Pulposus	Isotropic, elastic hex elements	9	0.4999
Annulus (Ground)	Hyperelastic, Neo Hooke	C10=0.3448, D10=0.3	
Annulus (Fiber)	Rebar	357-550	0.3
Ligaments			
Anterior Longitudinal	Truss elements	7.8 (<12%), 20.0 (>12%)	0.3
Posterior Longitudinal	Truss elements	10.0 (<11%), 20.0 (>11%)	0.3
Ligamentum Flavum	Truss elements	15.0 (<6.2%), 19.5 (>6.2%)	0.3
Intertransverse	Truss elements	10.0 (<18%), 58.7 (>18%)	0.3
Interspinous	Truss elements	10.0 (<14%), 11.6 (>14%)	0.3
Supraspinous	Truss elements	8.0 (<20%), 15.0 (>20%)	
Capsular	Truss elements	7.5 (<25%), 32.9(25%)	0.3
Apophyseal Joints	GAPUNI		

2.2. Boundary and Loading Condition

The nodes on upper end-plate of L1 were coupled to a flying node above the surface. The flying node was subjected to 10Nm pure moment in all six planes of motion, that is, flexion (Flex), extension (Ext), left and right axial rotation (AR), and left and right lateral bending (LB). The nodes on lower end-plate of L5 were constrained in all directions. 400N follower load was applied using wire elements at each motion segment, 200 on each side, in such a way that unwanted segmental rotation remained less than 0.2 degree. The FE model was validated against *in vitro* published values for flexion, extension, axial rotation (Panjabi et al., 2007) and lateral bending (Berkson et al., 1979).

3. Results

FE model was validated in all six planes of motion using *in vitro* range of motion values. Figure 1 shows comparison of *in vitro* and FE model predicted values of range of motion for six planes of motion. The validated lumbar FE model was subjected to pure moment in six motion planes. Facet loads (FL), interdiscal pressure (IDP), and loading for interspinous ligament (ISL) and capsular ligaments (CL) were predicted for L4-L5 motion segment.

FL was highest in extension and axial rotation where FL reached 200N on at least one side of facet joints. Flexion had least effect on FL as loads were less than 25N on either side of facet joints. In left lateral bending, 21N and 79N were predicted for left and right facets, respectively. In right lateral bending, 67N and 21N were predicted for left and right facets, respectively.

Maximum IDP was predicted for L4-L5 disc nucleus in each motion plane. The least IDP of 0.90MPa was predicted for extension motion. For flexion motion, it increased significantly to 1.67MPa. Similarly, left and right axial rotations had IDP of 1.42MPa. The highest IDP was predicted for lateral bending where predicted IDP rose to 2.14MPa and 2.31MPa for left and right lateral bending motion, respectively.

Two ligaments were investigated for load sharing analysis. For interspinous ligament (ISL), the highest stress of 3.27MPa was predicted in flexion motion followed by 0.7MPa in axial rotation. There was insignificant effect of ISL in extension and lateral bending (<0.001MPa). Capsular ligaments (CL) had considerable effect in flexion motion where highest stress of 29MPa was predicted. Extension had moderate effect on CL, with maximum stress of 20.7MPa. Left AR had maximum predicted stress of 21MPa while right AR had maximum predicted stress of 30MPa on CL. In left lateral bending, the predicted stress on CL was 16MPa which decreased significantly to 0.6MPa in right lateral bending.

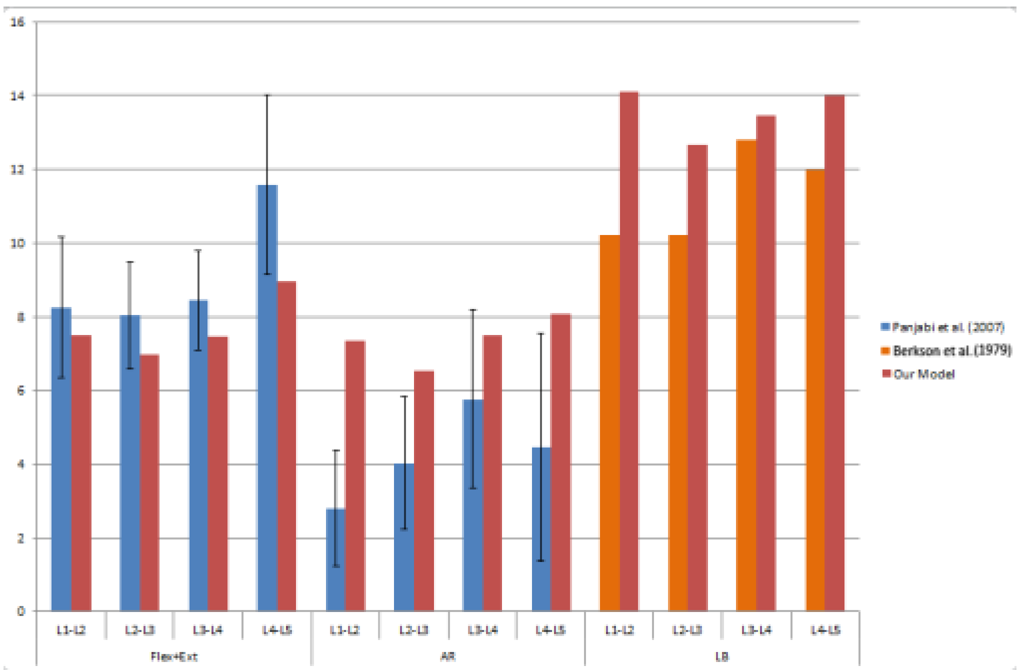

Fig. 1. Comparison of in vitro and FE values.

4. Discussion

Kiapour et al. (2012) investigated effect of facetectomy on a FE lumbar spine and concluded that only extension motion and axial rotation are significantly affected by facet removal. Sharma et al. (1995) reported results of facet removal on flexion and extension motion. Their FE model predicted moderate facet stresses in flexion because of resistance provided by capsular ligaments. For extension, they reported high facet stresses due to contact between articular surfaces. Similarly, our results predicted that facet joints were loaded to significant values in extension and axial rotation only.

Panjabi et al. (1984) performed cadaver testing of effect of discectomy on mechanical behavior of lumbar. Their results showed that nucleus removal strongly affects the flexion and right lateral bending motion with moderate effect in axial rotation and minimal change in extension. The results predicted by our FE model have positive correlation with *in vitro* test data. Lateral bending exerts most pressure on intervertebral disc nucleus, followed by flexion. Therefore, it can be concluded that these two motion planes transfer most load to disc nucleus.

Sharma et al. (1995) discussed role of posterior ligaments in their FE model study. Their investigation concluded that flexion motion has significant dependence on ligaments, especially ISL and CL. In extension motion, there was limited effect of CL removal alone. However, when facets were removed along with CL, it produced a large increase in extension motion. Hence, it was proposed by Sharma et al. (1995) that ISL in flexion and CL in flexion transfer most of the load.

5. Conclusion

This study has investigated the biomechanical parameters of lumbar FE model. Facet joint loading, intradiscal pressure, and stresses in ISL and CL were predicted. Based on this analysis, further studies can be carried out for addressing the problem of degeneration associated with lumbar spine.

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