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Original Investigation

Biomechanical Effect of Graded Facetectomy on Asymmetrical Finite Element Model of the Lumbar Spine

Aşamalı Fasetektominin, Gerçek (Asimetrik) Omurga Sonlu Eleman Modelinde Biyo-Mekanik Etkileri

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ABSTRACT

AIM: Facetectomy is a leading surgical method for stenosis treatment. The objective of this study was to investigate biomechanical effect of graded facetectomy on the lumbar spine using an asymmetrical finite element model.

MATERIAL and METHODS: A validated 3-dimensional asymmetrical finite element model of lumbar L1-L5 was developed based on computerized tomography (CT) scans. All components were assigned material properties mimicking original spinal components. Graded facetectomy was performed by removing facet elements along with surrounding capsular ligaments.

RESULTS: All three planes of motion were simulated and resulting range of motion at the index level, L4-L5, was compared with the intact model. Left unilateral facetectomy caused increase in range of motion by 14.6%, 87.4%, 94.5%, 10.5%, 6.3% and 8.8% for flexion, extension, left and right axial rotation, and left and right lateral bending, respectively. Total bilateral facetectomy resulted in an increase in motion by 33.6%, 238.7%, 120.4, 151.3%, 15.6% and 12.4% for flexion, extension, left and right axial rotation, and left and right lateral bending, respectively.

CONCLUSION: Extension and axial rotation were found to be affected by the facet removal whereas flexion and lateral bending were mildly affected.

KEYWORDS: Facetectomy, Lumbar spine, Finite element model

ÖZ

AMAÇ: Stenoz hastalığı için yapılan ameliyatların başında fasetektektomi gelmektedir. Amaç, sonlu eleman yöntemiyle oluşturulan lomber model üzerinde aşamalı olarak gerçekleştirilen fasetektominin omurga biyomekaniğine etkisini araştırmaktır.

YÖNTEM ve GEREÇLER: Valide edilmiş 3 boyutlu asimetrik sonlu eleman lomber modeli (L1-L5) oluşturulmuştur. Bu model bir insan CT görüntüsü kullanılarak elde edilmiştir. Omurga modelinde bulunan yumuşak dokular ve kemik malzeme özellikleri literatürden alınmıştır. Aşamalı fasetektomi, faset eklemlerinin ve bu eklemi sarmalayan kapsüler ligamentlerin modelden çıkarılmasıyla elde edilmiştir.

BULGULAR: Her bir üç hareket düzlemi üzerinde analizler yapılmıştır ve sonuç olarak ameliyat edilen segmente, L4-L5, meydana gelen hareketler ameliyat öncesi ve sonrası olmak üzere karşılaştırılmıştır. Sol unilateral fasetektomi hareketin artmasına neden olmuştur: %14,6-fleksiyon, %87,4-ekstensiyon, %94,5-sol eğilme, %10,5-sağ eğilme, %6,3-sol dönme ve %8,8-sağ dönme. Tam bilateral fasetektomi aynı şekilde hareketin artmasına neden olmuştur: %33,6-fleksiyon, %238,7-ekstensiyon, %120,4-sol eğilme, %151,3-sağ eğilme, 15,6%-sol dönme ve 12,4%-sağ dönme.

SONUÇ: Lomber bölgede yapılan fasetektomi ameliyatından en çok etkilenen hareketler ekstansiyon ve aksiyel rotasyon olurken, fleksiyon ve yana eğilme hareketleri daha az etkilenmiştir.

ANAHTAR SÖZCÜKLER: Fasetektomi, Lomber omurga, Sonlu eleman modeli

INTRODUCTION

Spinal stenosis is the narrowing of spinal canal, causing pain and loss of motor control for certain parts of body. The prevalent physiopathology of stenosis includes intervertebral disc bulging, facet thickening and ligamentum flavum hypertrophy (2). The most common treatment involves dorsal decompression, that is, the opening of spinal canal through facetectomy and laminectomy. Depending on the extent of stenosis, the surgery can either be hemifacetectomy or laminectomy and, in each case, either mono- or bi-lateral (18). Facetectomy tends to create greater spinal instability and increases deformation of vertebra. The exact degree of instability caused by these surgical methods helps in deciding about fusion of vertebras.

In order to analyze effect of facetectomy on lumbar, *in vitro* studies are standard technique for several years. Using experimental set up, Abumi et al. (1) analyzed lumbar spinal stability by performing unilateral and bilateral, medial and total facetectomies. Results of their study showed positive correlation between severity of facet injury and range of motion (ROM) for flexion and axial rotation. Okawa et al. (10) performed cadaveric study to examine the effect of partial laminotomy and facetectomy on the lumbar segmental stability. They carried out Cyclic loading tests in compressive and bending directions with unilateral and bilateral facetectomy. Their results showed insignificant effect of facetectomy on flexion and lateral bending. Yue et al. (19) performed *in vitro* and *in vivo* study and concluded that lumbar instability significantly increased after 50% graded facetectomy. However, *in vitro* experiments pose several shortcomings. There are variations in bone quality, the lumbar area may be diseased or coming from old age individual and can be virus infected (7). Moreover, cadaver segments are not reproducible for multiple experiments.

An alternative biomechanical model for *in vitro* models is finite element mesh (FEM) model which has become a popular method for analyzing lumbar motion segments. A number of FE models have been proposed in literature. Lee and Teo (6) studied the effects of laminectomy and facetectomy on the stability of the L2-L3 lumbar motion segment using FEM model. They reported an increase in lumbar kinematics, leading to lumbar instability under total bilateral laminectomy coupled with facetectomy. Bresnahan et al. (2) performed graded removal of posterior elements in FEM model at L3-L4 and L4-L5 for stenosis treatment and reported increase in flexion-extension and axial rotation motion with increase in removal of posterior elements. Open laminectomy was simulated at L4 of FEM model by Ogden et al. (9). Their findings showed an increase in motion due to flexion, extension and axial rotation whereas no significant change in lateral bending. Although these early computational models made significant contribution towards lumbar kinematics, they had several limitations. Most of these models were symmetrical (18)(6)(5), that is, left and right halves of a lumbar segment is same along mid-sagittal plane. In contrast, real human spine is asymmetric, that is, left and right halves of a vertebra shows considerable differences and, hence, symmetrical models are not realistic enough.

The aim of the present study was to develop a complete asymmetric FE model of lumbar spine (L1-L5) using hexahedral mesh. The geometry of proposed model was asymmetric along mid-sagittal plane, resulting in realistic analysis. Validation of model was carried out using cadaver studies. The model was subjected to graded facet injuries and effect of each injury was determined and compared with published *in vitro* and FE studies.

MATERIAL and METHODS

Finite Element Model of the Intact L1-L5 Lumbar Spine

A three-dimensional, nonlinear finite element (FE) model of L1 through L5 was used in this study. Computed tomography (CT) scan data of a 35 years old healthy man was used to develop the model. The FE lumbar model is asymmetric across mid-sagittal plane and consists of 72193 nodes and 55650 elements. The model was developed as a sequence of steps which have been explained in our previous work (3). Briefly, image processing software (Mimics® Version 14.1; Materialise, Inc., Leuven, Belgium) was used to process CT Data of lumbar spine. Discs were created manually because CT scan data does not identify spinal discs. Once L1-L5 lumbar with accompanying discs had been created, mesh creation on the surfaces was carried out by using IA-FEMESH software (University of Iowa, IA). Hexahedral mesh was generated on the vertebra and disc surfaces previously created. Radial mesh was created for discs and anterior part of vertebra. Finally, the hexahedral mesh was imported to (ABAQUS®, Version 6.10-2; Abaqus, Inc., Providence, RI, USA). All lumbar parts were merged with each other, and ligaments and facet joints were attached to the model. Figure 1 shows the complete developed lumbar FE model.

Vertebra

Each vertebra consists of two major components: Vertebral body and Posterior spinal processes. Vertebral body is formed

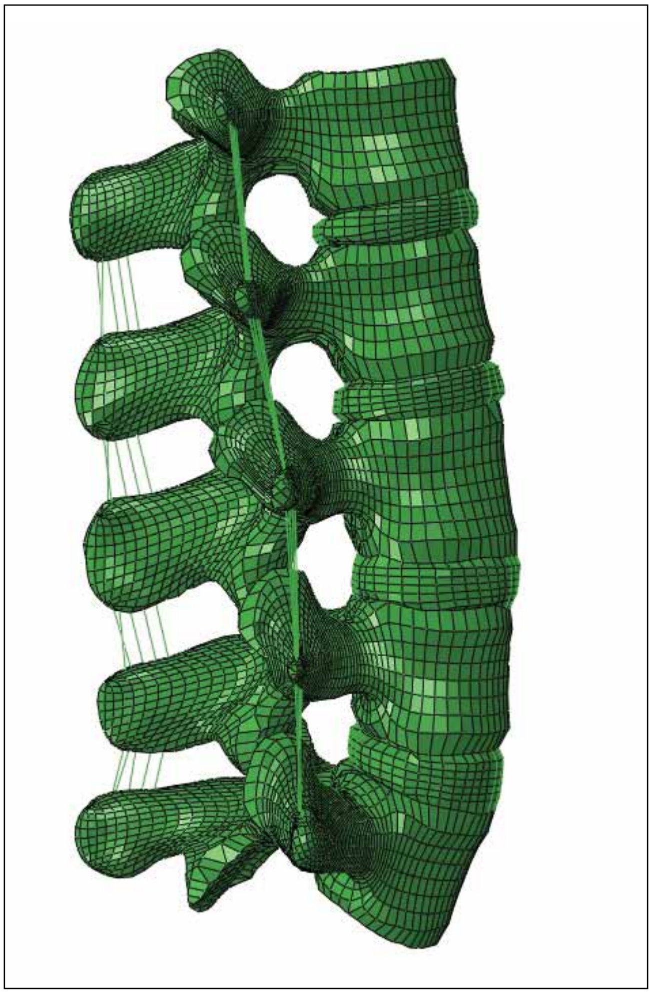

Figure 1: Finite element mesh model of lumbar spine, L1 through L5.

by Cancellous bone core encapsulated by thick Cortical bone. Cortical bone is in direct contact with vertebral discs. In our FE model, the top and bottom surfaces of cortical bone are merged with vertebral discs. Posterior part of lumbar consists of 9 processes with ligaments attached on their surfaces.

Intervertebral Disc

Intervertebral discs consist of incompressible nucleus pulposus surrounded by composite structure of annulus fibrosus. Nucleus consists of approximately 35% of total disc volume. The annulus consists of concentric layers of fibrous cartilage. Circular mesh was created on the disc model in order to simulate concentric rings. Neo-Hookean hyperelastic model was used to simulate the annulus fibrosus ground substance material. In our model, three rings of ground substance were present. Each ring contains two evenly spaced fiber layers (REBAR) at ±30° to the horizontal.

Ligament and Facet Joints

Ligaments were simulated by truss elements having nonlinear hypo-elastic property. Seven types of ligaments were assigned to the model: Anterior Longitudinal (ALL), Posterior Longitudinal (PLL), Ligamentum Flavum(LF), Intertransverse (ITL), Interspinous (ISL), Supraspinous (SSL) and Capsular (CL). Each ligament type has distinct cross-sectional area. In each segment, 9, 5, 4, 8, 3, 2 and 16 truss elements were used to simulate each of ALL, PLL, LF, ITL, ISL, SSL and CL, respectively. These truss elements were assigned non-linear material properties, having low stiffness at low strains with increase in stiffness at higher strains. Table I shows detailed mechanical properties of each of these ligaments.

Facet joints were defined using three-dimensional unidirectional Gap (GAPUNI) elements. Briefly, these elements are responsible for transferring force between nodes in the same direction as function of specified gap between them (3). ABAQUS's "softened contact" parameter simulated cartilaginous layer between the facet surfaces. This adjusts force transfer across the joint in relation with size of the gap.

Material Properties

Material properties of the individual components were defined based on literature values (3, 5, 17) with some modifications to fit asymmetrical model. Vertebral mesh was divided into groups of cancellous bone, cortical bone, posterior parts and endplates (17) based on differences in their mineral density. Table I summarizes these properties.

Boundary and Loading Conditions

Before the simulating model, the bottom layer of L5 was fixed. A 400N follower load was applied using connector wire elements. Two wires were put at each level, each applying 200N load. Change in ROM with and without follower load was measured to confirm that wires pass through center

Table I: Material Properties of Components of Lumbar FE Model

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		

of rotation at each lumbar segment. A difference of 0.2° is acceptable (11). The wires were placed such that there is no buckling or bending in the model. The next step involved applying a 10Nm bending moment to the top surface of L1 vertebra in each moment plane, that is, flexion, extension, axial rotation (AR) and lateral bending (LB). Change in ROM was measured for each case and compared with literature values (5). Boundary conditions and all loads were kept same for intact and injured models.

Destabilized Model

The intact model was modified at L4-L5 level to create four injured cases, as listed below:

1) 50% unilateral medial facetectomy (UF-50);
2) 75% unilateral medial facetectomy (UF-75);
3) total left unilateral medial facetectomy (UF-T);
4) total bilateral facetectomy (BF-T).

In order to remove facets, surrounding CL had to be removed since they encapsulate the facets (18). The facet removal was initiated from lower portion of facet joint to create partial removal. The process continued towards upper part of facet joint, culminating in complete facet removal.

RESULTS

Validation

The FE model for L1-L5 lumbar was validated against the *in vitro* results published in literature (8, 13, 14, 16). The comparison between FE and *in vitro* ROM values is shown in Table II. Since our FE model is asymmetric, both left and right axial rotation and lateral bending were validated separately. For flexion motion, the resulting ROM values of our FE model were generally stiffer than the values of Yamamoto et. al (16). ROM values for extension motion were in the range of *in vitro* values of Schmoelz et. al. (14) and Yamamoto et. al (16), except for L2-L3 motion segment. In case of lateral bending, ROM values of FE closely followed values of (16) and (14), with left lateral bending ROM stiffer than the right. Similarly, for axial rotation motion, FE ROM values were flexible than *in vitro* ROM values of (16) and (14).

Table II: Validation of Lumbar FE Model Against Cadaver Studies

	Flexion (°)	Extension (°)	Lateral Bending (°)	Axial Rotation (°)
L1-L2				
Yamamoto et. al (Yamamoto et al., 1989), 10Nm	5.8±0.6	4.3±0.5	4.7±0.4 (L) 5.2±0.4 (R)	2.6±0.5 (L) 2.0±0.6 (R)
Present Study, 10Nm	3.40	4.07	6.69 (L) 7.01 (R)	3.89 (L) 3.47 (R)
L2-L3				
Schmoelz et al (Schmoelz et al., 2003), 10Nm	4.3±1.0	4.6±2.2	5.4±2.2	1.0±1.0
Yamamoto et. al (Yamamoto et al., 1989), 10Nm	6.5±0.3	4.3±0.3	7.0±0.6 (L) 7.0±0.6 (R)	2.2±0.4 (L) 3.0±0.4 (R)
Present Study, 10Nm	4.11	2.89	5.95 (L) 6.37 (R)	3.17 (L) 3.37 (R)
L3-L4				
Niosi et al (Niosi et al., 2006), 7.5Nm	4.4 ±2.0	2.4 ± 0.9	2.4 ± 1.2	1.2 ±0.5
Schilling et al (Schilling et al., 2011), 7.5Nm	4.67±1.79	2.18±0.54	7.66 ±2.91	4.67 ±2.52
Schmoelz et al (Schmoelz et al., 2003), 10Nm	5.0±1.0	4.0±1.3	4.7±2.0	1.0±0.6
Yamamoto et. al (Yamamoto et al., 1989), 10Nm	7.5 ±0.8	3.7 ±0.3	5.7 ±0.3(L) 5.8 ± 0.5(R)	2.7 ± 0.4 (L) 2.5 ±0.4 (R)
Present Study, 10Nm	3.74	3.70	6.24 (L) 7.34 (R)	3.68 (L) 3.80 (R)
L4-L5				
Schilling et al (Schilling et al., 2011), 7.5Nm	5.62 ±2.17	3.32±1.12	7.76 ±1.85	5.16±1.30
Yamamoto et. al (Yamamoto et al., 1989), 10Nm	8.9 ±0.7	5.8 ±0.4	5.5 ±0.5(L) 5.9 ±0.5(R)	1.7±0.3 (L) 2.7±0.5 (R)
Present Study, 10Nm	5.50	3.45	6.62 (L) 7.08 (R)	4.08 (L) 3.98 (R)

Table III: Range of Motion for L4-L5 Lumbar Segment After Graded Facetectomy

L4-L5	Flexion (˚)	Extension (˚)	Left AR (˚)	Right AR (˚)	Left LB (˚)	Right LB (˚)
Intact	5.50	3.45	4.08	3.98	6.62	7.08
50% Left Unilateral	6.17	4.18	4.41	4.40	7.03	7.21
75% Left Unilateral	6.17	4.65	4.77	4.40	7.03	7.28
Total Left Unilateral	6.30	6.47	7.94	4.40	7.04	7.70
Total Bilateral	7.35	11.69	8.99	10.00	7.65	7.96

Range of Motion

The effect of graded facetectomy on the ROM of lumbar spine was analyzed. Table III summarizes the value of rotation angles for each motion plane for intact and injured L4-L5 motion segment (see Methods for injured cases). In flexion motion, the rotation increased by 14.6% for UF-T at L4-L5. For extension, the three injury levels of UF-50, UF-75 and UF-T resulted in increase in rotation by 21.2%, 34.9% and 87.4%, respectively. Similarly, a large increase of 94.5% in motion was observed for left AR as compared to a small increase of 10.5% for right AR after UF-T. LB showed little increase as less than 8% change is recorded for both left and right LB in case of UF-T. The analysis was extended to BF-T and an increase in rotation of 33.6%, 239%, 120%, 151%, 15.6% and 12.4% for flexion, extension, left AR, right AR, left LB and right LB, respectively, was observed with respect to intact case.

DISCUSSION

This study was aimed at generating a hexahedral mesh for complete lumbar spine, L1 through L5. To ensure realistic results, the vertebral and disc asymmetry about the mid-sagittal plane was retained. The asymmetry was a distinct feature of our model, differentiating it from previously proposed symmetrical FE models (5, 6, 18). The proposed models in the literature had inherent simplifications in design which made their analysis not realistic enough. The present model was constructed using the CT scans to ensure accurate geometry for vertebrae.

The full lumbar model was validated against *in vitro* experimental studies to ensure suitability of model for further analysis. All six planes of motion were considered for validation. The predicted ROM values in extension closely followed cadaver values. However, for flexion, the FE model had stiffer values than *in vitro* studies. Moreover, in lateral bending and axial rotation, a large deviation in ROM compared with *in vitro* values of Yamamoto et al. (16) was observed. A couple of reasons have been suggested for this behavior. Firstly, intervertebral discs show variable levels of degradation in cadaver testing (18). Disc plays a significant load sharing role in lateral bending, axial rotation and flexion motion (12) and any degradation in disc will result in different ROM. In our FE model, it was not possible to apply varying degrees of degradation in disc and, hence, difference between *in vitro* and predicted values was observed. Secondly, most of the *in vitro* studies are performed using cadavers belonging to old age people who have several prominent degenerations in lumbar segments (18).

In order to investigate effect of facet injury on segmental stability of lumbar, the FE model was subjected to graded facetectomy in four stages at L4-L5 motion segment (6). The effect of injury on spinal stability varied according to extent of injury and motion plane. According to results predicted by our asymmetrical FE lumbar model, for all motion planes, except extension, partial facetectomy did not result in any significant change in motion and change in ROM remained below 12% for both UF-50 and UF-70. Tensile stress in CL keeps facets in stressed mode and, hence, limits their ROM. Since surrounding CL were removed when facetectomy was being done, this led to increase in motion for partial facetectomy.

Only extension motion was significantly disturbed by partial facetectomy. The motion increased as much as 87% in extension when total unilateral facetectomy was carried out on L4-L5. Furthermore, motion increased by 239% when L4-L5 was subjected to total bilateral facetectomy. Such drastic increase in extension motion was also reported by Sharma et al. (15) who performed FE study on role of facets. According to their findings, at moments above 4Nm, movement of facet joints is restricted which provide stiffness to the segment and keep the motion within psychological limits. In case of any injury to facets, the extension motion becomes abnormally high for large moments. Similarly, Kiapour et al. (5) carried out FE study to analyze the effect of facet removal. Their results showed increase of 222% in extension for facetectomy. However, they did not comment on status of CL during facet removal. Moreover, their analysis did not consider complete lumbar model and the asymmetry in lumbar motion segments was not retained.

Similarly, for axial rotation, our predicted results showed significant increase in ROM for unilateral and bilateral total facet removal. Abumi et al. (1) performed an *in vitro* facetectomy study and concluded that ROM increased significantly for axial rotation, depending on the extent of injury. Moreover, they suggested that, for unilateral total facetectomy, increase in ROM occurs in opposite direction for axial rotation. Our predicted results also show similar behavior in axial rotation. In case of lateral bending, the predicted change is less than 15% even after total bilateral facetectomy. Therefore, it is concluded that facet removal of any degree does not have particular effect on ROM of lumbar spine in lateral bending. Several other studies present in literature hold similar view (18, 1).

One of the distinctive geometric feature of our model is the location of facet planes which were not symmetric about the mid-sagittal plane, unlike models proposed in the literature (5, 6, 18). This asymmetry led to coupled motion, particularly in extension plane, as described in our previous work (3). The addition of coupled motion is significant in future works such as implantation of dynamic devices in the lumbar motion segment. In these scenarios, coupled motion can have significant effect on the motion of lumbar in a particular motion plane.

CONCLUSION

The objective of current study was to develop an asymmetric lumbar FE model and use it to analyze the effect of facetectomy on lumbar kinetics. Absence of complete and asymmetric lumbar FE model in literature was a driving factor behind current study. The FE model was subjected to multiple injury cases and ROM values were predicted. Motion values were compared with *in vitro* and symmetric FE model studies. The stability of motion segment was lost after total facet removal as ROM increased significantly, especially in extension and axial rotation. For flexion and lateral bending, no remarkable change in ROM was predicted. Based on these results, the surgery and resection of facetectomy should be limited when spinal stenosis is being treated. Further treatment involving fusion or screws might be needed depending on the extent of resection.

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