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Does Disc Space Height of Fused Segment Affect Adjacent Degeneration in ALIF? A Finite Element Study

ALİF de Füzyon Yapılan Segmentin Disk Mesafesi Yüksekliği Komşu Seviye Dejenerasyonunu Etkiler mi? Bir Finite Element Çalışması

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ABSTRACT

AIM: The restoration of disc space height of fused segment is essential in anterior lumbar interbody fusion, while the disc space height in many cases decreased postoperatively, which may adversely aggravate the adjacent segmental degeneration. However, no literature available focused on the issue.

MATERIAL and METHODS: A normal healthy finite element model of L3-5 and four anterior lumbar interbody fusion models with different disc space height of fused segment were developed. 800 N compressive loading plus 10 Nm moments simulating flexion, extension, lateral bending and axial rotation were imposed on L3 superior endplate. The intradiscal pressure, the intersegmental rotation, the tresca stress and contact force of facet joints in L3-4 were investigated.

RESULTS: Anterior lumbar interbody fusion with severely decreased disc space height presented with the highest values of the four parameters, and the normal healthy model presented with the lowest values except, under extension, the contact force of facet joints in normal healthy model is higher than that in normal anterior lumbar interbody fusion model. With disc space height decrease, the values of parameters in each anterior lumbar interbody fusion model increase gradually.

CONCLUSION: Anterior lumbar interbody fusion with decreased disc space height aggravate the adjacent segmental degeneration more adversely.

KEYWORDS: Anterior lumbar interbody fusion, Adjacent segmental degeneration, Disc space height, Segmental lordosis

ÖZ

AMAÇ: Anterior lomber interbody füzyonda füzyon yapılan segmentin disk mesafesi yüksekliğinin korunması gerekli olmasına rağmen birçok vakada disk mesafesi yüksekliği postoperatif azalmaktadır ve bu da komşu seviye dejenerasyonunu olumsuz olarak artırabilmektedir. Bununla birlikte bu konuya odaklanmış hiçbir literatür yoktur.

YÖNTEM ve GEREÇ: Normal sağlıklı bir L3-5 finite elemen modeli ve füzyon yapılan segmentin disk mesafesi yüksekliğini değişik olan dört anterior lomber interbody füzyon modeli oluşturuldu. L3 üst sonplaklarına fleksiyon, ekstensiyon, yana eğilme ve aksiyel rotasyon şeklinde 800 N kompresif yüklenme artı 10 Nm momentler uygulandı. L3-4 deki disk içi basınç, intersegmental rotasyon, tresca stresi ve faset eklemlerin kontak kuvvetleri araştırıldı.

BULGULAR: Disk mesafesi yüksekliği ciddi biçimde azalmış olan anterior lomber interbody füzyon dört parametrenin hepsinde en yüksek değerlere sahipken ve normal sağlıklı model en düşük değerlere sahipti. Sadece ekstensiyon altında normal sağlıklı modelde faset eklemlerin kontak kuvvetleri normal anterior lomber interbody füzyon modelindekilerden yüksekti. Disk mesafesi yüksekliği azaldıkça her bir anterior lomber interbody füzyon modelinde parametrelerin değerleri artmakta idi.

SONUÇ: Disk mesafesi yüksekliği azalmış anterior lomber interbody füzyon komşu seviye dejenerasyonunu olumsuz yönde artırır.

ANAHTAR SÖZCÜKLER: Anterior lomber interbody füzyon, Komşu seviye dejenerasyonu, Disk mesafesi yüksekliği, Segmental lordoz

INTRODUCTION

Anterior lumbar interbody fusion (ALIF) has been widely used in recent years to treat a variety of spinal diseases, which relieve pain and improve functional status by distracting the affected degenerated segment, placing the interbody fusion devices, and stabilizing the motion segment of degenerative lumbar segments. The restoration of disc space height (DSH) is essential in ALIF to decompress intervertebral foramen, relax nerve roots and relieve symptoms. The reduction of DSH of fused segments, resulted from inserted improper cage or cage subsidence, may alter the mechanical status and adversely affect the clinical result.

Many authors reported on the disadvantage of the reduction of DSH after ALIF (7,4,12,19,23) and suggest subsidence will adversely affect the foraminal size and correction of mechanical deformity (7,3,26). Although only a small number of patients with decreased DSH need surgical treatment, in our opinion, the reduction of DSH may decrease the lordosis of lumbar spine and change the situation of stress conduction of lumbar segments, which may prompt the long-term complications of ALIF, ie, the adjacent segment degeneration. However, up to now, no literature available focused on the correlation between DSH reduction and adjacent segment degeneration in ALIF.

Nevertheless, inherent limitations in clinical research and conventional experiments make it significantly difficult to study on the issue. Specimens for cases and controls are difficult to obtain and standardize, and subsequent repetitive testing under various loads can result in significant sample variability. In contrast, the finite element modeling technique mitigates these problems. It is highly reproducible and repeatable. Adjustments can be made to the models to affect the material properties, simulate different situations of spine either in normal or fusion conditions with different DSH, show stress distribution under different loading modes, or reflect any structural change (2). Compared with other experimental methods, the finite element method has many advantages, facilitating a comparative study among different models.

Therefore, we embarked on a study of finite element analysis to assess the correlation between adjacent segmental degeneration and different DSH in ALIF.

MATERIAL and METHODS

A three-dimensional numerical model of a two-level ligamentous lumbar segment (3 vertebrae and 2 discs) was built and implemented with the finite element model (FEM) software ANSYS 10.0. Five different configurations of the model were considered: (1) a normal healthy model of L3-5; (2) an ALIF model with mildly decreased DSH; (3) an ALIF model with moderately decreased DSH; (4) an ALIF model with severely decreased DSH; (5) a normal ALIF model. The decreased DSH models and normal ALIF model were modified from the normal model by changing geometry or material properties of the L4-5 segment. We assume the elements of the L3-4 segments including intervertebral disc, facet joints, endplates, and vertebral bodies to be normal in all finite element models.

1. Normal model

A non-linear, three-dimensional FEM of L3-5 was created with geometry based on the high resolution computed tomography scan (slice thickness of 0.75mm) of a 26-year-old healthy male volunteer. The FEM of the ligamentous lumbar spine consisted of vertebrae, intervertebral discs, endplates, superior and inferior facet articulating surfaces, ligaments and capsules. Spinal structures that could not be recognized using computer tomography were determined by magnetic resonance imaging and histological observations (20).

The modeled vertebrae and intervertebral discs were meshed using eight-node solid 186 elements. The vertebrae and intervertebral discs model consists of 156806 elements and the seven spinal ligaments were represented by 2-node link 10 elements, which do not offer resistance in compression. The surfaces of facet joints were simulated by a cartilaginous layer, which was assumed to be multi-linear elastic in compression. The contact between the facet joints was simulated by surface to surface contact elements without friction. The facet joints have a gap of 0.5 mm and can only transmit compressive forces.

The intervertebral discs consisted of the nucleus pulposus and the surrounding annulus fibrosus. The nucleus pulposus, modeled as an incompressible material, was 43% of the total disc volume and located slightly posterior to the center of the disc (28). The annulus fibrosus was assumed to be a composite of a homogenous ground substance reinforced by collagen fibers. Seven crisscross fiber layers were defined in radial direction and the fibers were mounted in two times seven layers with orientation of $\pm 30^{o}$ to the midcross-sectional plane. The fiber content of the modeled annulus fibrosus was approximately 19%, appropriate to the natural collagen content of the annulus. The material constants for the nucleus and annulus ground substance were defined according to previously accepted values (8) (Table I).

2. The normal ALIF model and ALIF models with decreased DSH

To mimic ALIF, the L4-5 disc of normal model was removed and replaced by the interbody bone graft, which was assumed to have the same dimensions as the healthy disc. The graft is assumed to have gained solid fusion, enabling the fusion mass to transmit loads in compression as well as in tension. Three different DSH ALIF model (mild, moderate, severe) were developed relative to the normal ALIF model. Compared to the normal ALIF model, the mildly, moderately, and severely decreased DSH had 20%, 40% and 60% less height respectively (18). In the normal healthy model and normal ALIF model the facet surfaces of L4-5 were oriented parallel and in the decrease DSH models the inferior facet of L4 became oblique to the superior facet of L5 because of decreased height (18). To facilitate the study, we assume that the fusion mass in four different ALIF models have the same material properties.

Table I: The Material Properties in the Finite Element Models

	Young's modulus (MPa)	Poisson's ratio	Element type	Element number	Cross-section (mm^2)
Cortical bone	12000	0.3	Solid186		
Cancellous bone	100	0.2	Solid186		
Fiber	92	0.45	Solid186		
endplate	500	0.25	Solid186		
Posterior elements	3500	0.30	Solid186		
Facet cartilage	3500	0.25	Solid186		
Nucleus pulposus	1	0.499	Solid186		
Annulus ground substance	4.2	0.45	Solid186		
capsular ligament	7.7	0.39	Link10	24	102.5
anterior longitudinal ligament	11.9	0.39	Link10	20	75.9
posterior longitudinal ligament	12.5	0.39	Link10	10	51.8
ligamentum flavum	2.4	0.39	Link10	6	78.7
interspinous ligament	3.4	0.39	Link10	6	36.3
supraspinous ligament	3.4	0.39	Link10	2	75.7
transverse ligament	3.4	0.39	Link10	10	2

3. Boundary and loading conditions

The degrees of freedom of inferior surfaces of L5 were completely fixed in all directions. To validate the model, a pre-compressive loading of 800 N was applied on the superior endplate of L3 of the normal healthy model. The loading-displacement curve was plotted and compared with the previous finite element studies from Skalli et al(22) and Chosa E(5). Then 10Nm flexion, 10Nm extension, 10Nm lateral bending, and 10Nm axial rotation moment under 800 N compressive loading were imposed on L3 superior endplate of all models respectively. The maximum load was achieved in five load steps in each model and the main parameters including the intradiscal pressure, the intersegmental rotation, the maximum tresca stress of annulus fibrosus and contact force of facet joints at L3-4 segment were investigated.

RESULTS

Our results from the normal healthy model were compared with those from Skalli et al and Chosa E. The similar biomechanical changes and agreement between our results and the reported data were found when compression loading increased (Figure 1), indicating the validity of our model.

The intradiscal pressure of L3-4 in different loads and models are displayed in Figure 2. Under all loading directions, the intradiscal pressure in the ALIF model with severely decreased DSH is the highest and presented with 0.52 Mpa, 0.43 Mpa, 0.267 Mpa and 0.27 Mpa in flexion, extension, lateral bending and axial rotation respectively, and the intradiscal pressure in normal healthy model is the lowest and presented with 0.23Mpa, 0.27Mpa, 0.14Mpa and 0.15Mpa in flexion, extension, lateral bending and axial rotation. In all loading directions, the intradiscal pressure in ALIF models increase gradually with DSH decreasing.

The intersegmental rotations of L3-4 in different models and loading directions are displayed in Figure 3. Under all loading directions, the intersegmental rotation of the ALIF model with severely decreased DSH is the largest with 7.1° in flexion, 5.1° in extension, 4.9° in lateral bending and 2.5° in axial rotation, and the intersegmental rotation of L3-4 in normal healthy model is the lowest with 5.1° in flexion, 3.1° in extension, 4.1° in lateral bending and 2° in axial rotation. Under extention, lateral bending and axial rotation, there is little difference in intersegmental rotations between moderately decreased DSH model and severely decreased DSH model.

The tresca stresses on the L3-4 annulus fibrosus in different models and loading directions are displayed in Figure 4. These are higher in the ALIF model with severely decreased DSH than in any of the other models in all loading planes with 1.57 MPa in flexion, 0.9 MPa in extention, 1.25 MPa in lateral bending, and 0.61 MPa in axial rotation. The normal healthy model has the lowest tresca stresses with 0.43 MPa in flexion, 0.46 MPa in extention, 0.68 MPa in lateral bending, and 0.17 MPa in axial rotation. The tresca stresses in different ALIF models are larger than the normal healthy model. With decrease of L4-5 DSH, the L3-4 tresca stresses increase gradually.

The contact force of facet joint of L3-4 in different models and loading directions are displayed in Figure 5. Under all loading directions, the contact force of facet joints is larger in the ALIF model with severely decreased DSH than any other models and presented with 96.8N, 80.9N and 81N in extention, lateral bending and axial rotation respectively. Under lateral bending and axial rotation, the contact force of facet joints in normal healthy model is lower than any other models. However, under extension, the contact force of facet joints in normal ALIF model (82.1N) is slightly lower than the normal healthy model (84.5N). The contact force of facet joint in L3-4 increase with the DSH of L4-5 decreasing.

DISCUSSION

A normal three-dimensional non-linear finite element model of L3-5 has been developed along with one normal ALIF model and three ALIF models with decreased DSH of L4-5. We attempt to determine if the decreased DSH of fused

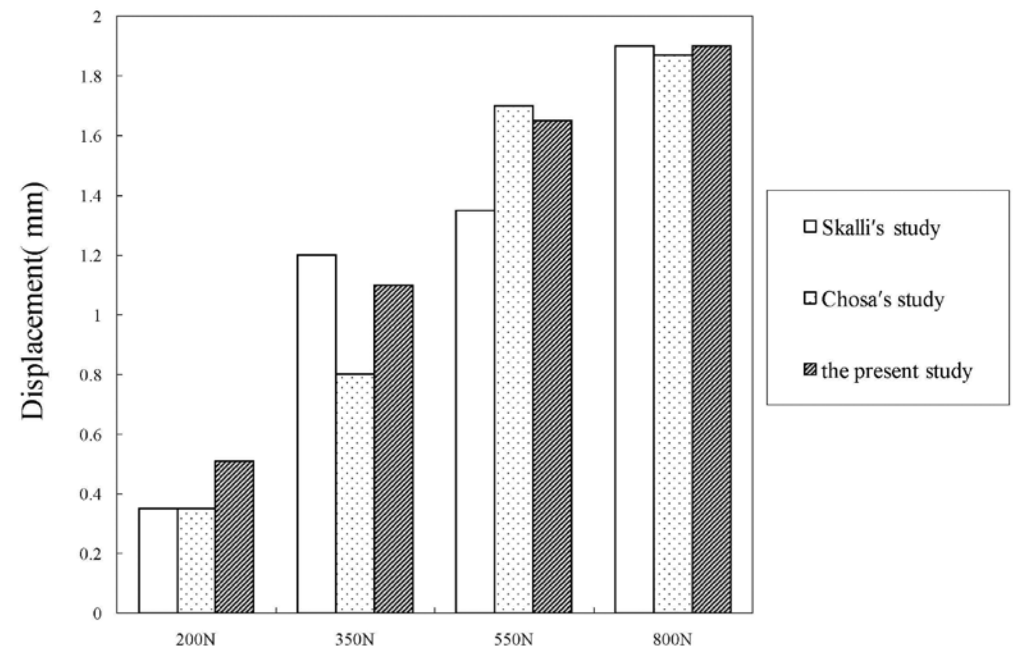

Figure 1: Model validation: comparison with results of the studies by Skalli and Chosa E.

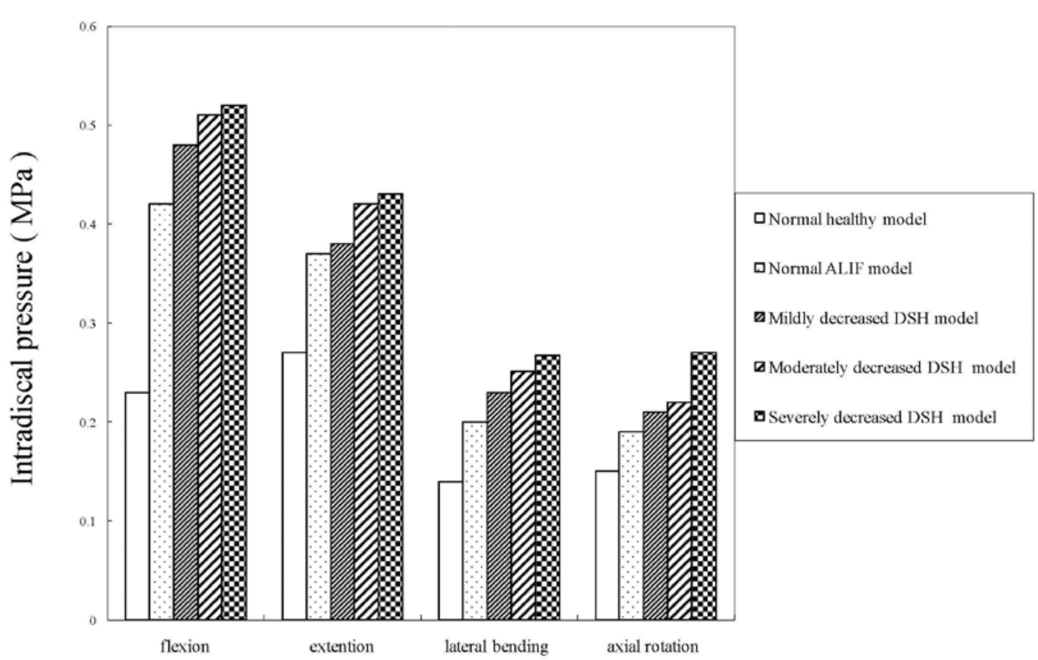

Figure 2: Intradiscal pressure in different loading directions and models.

segment may aggravates adjacent segment degeneration, by comparing the parameters of intradical pressure, intersegmental rotation, tresca stress and contact force of facet joints.

With widely used in clinical practice, one potential complication of ALIF, adjacent segmental degeneration (ASD), has become much more widespread (13,15,25). Fusion results in increased stiffness and stress concentration, and the adjacent levels compensate for the segmental immobility and the forces are redistributed. The loads generated from the body weight and muscle strains are partially shifted to the remaining mobile segments, resulting in earlier degenerative

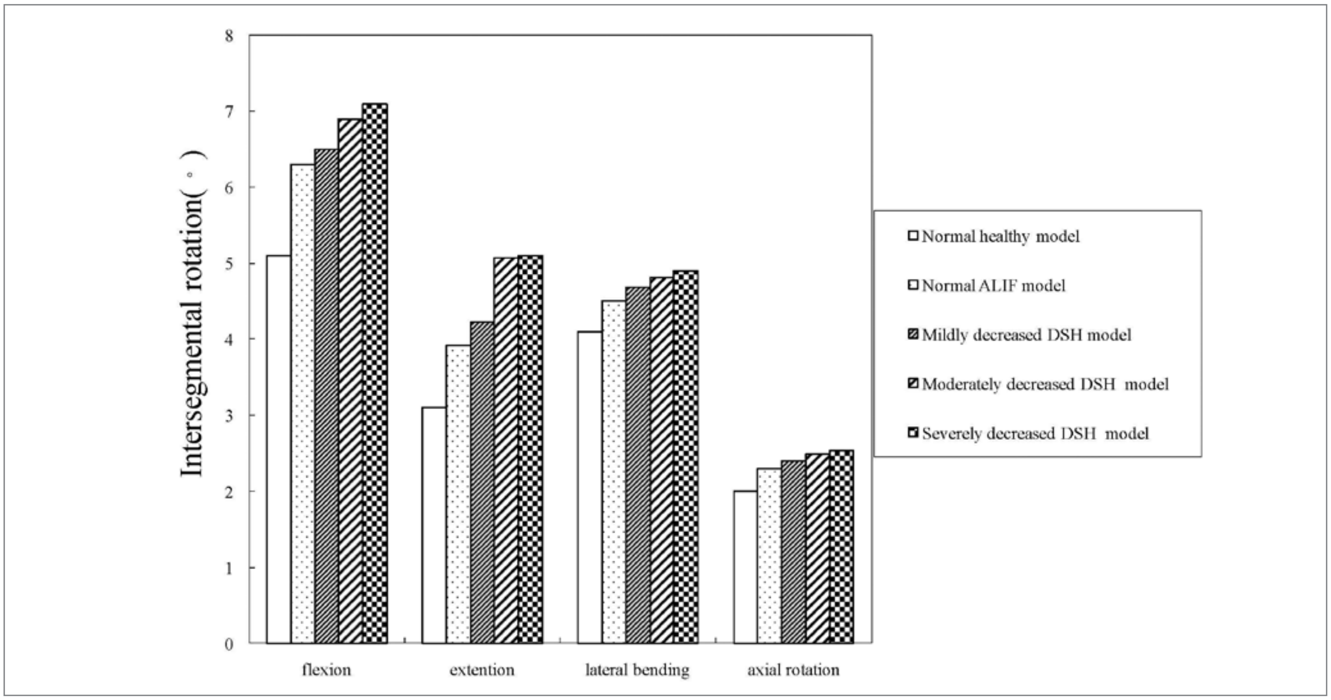

Figure 3: Intersegmental rotations in different loading directions and models.

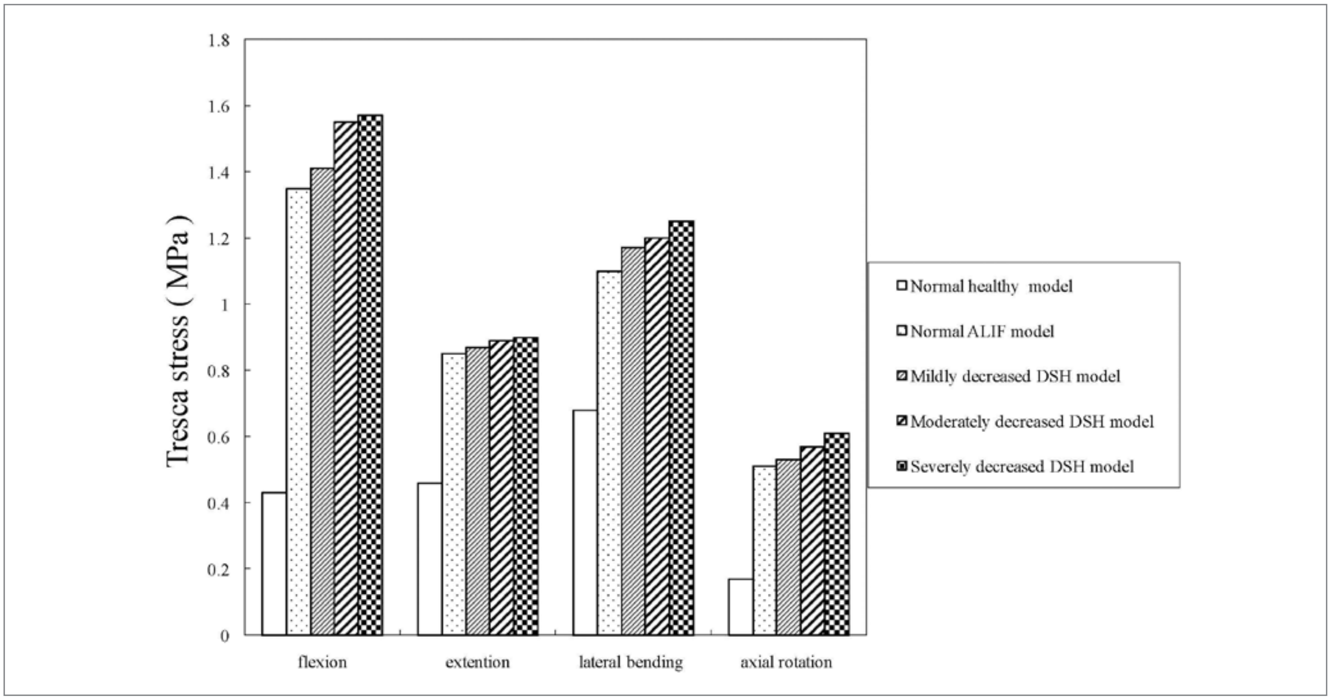

Figure 4: Tresca stress on annulus fibrosus in different loading directions and models.

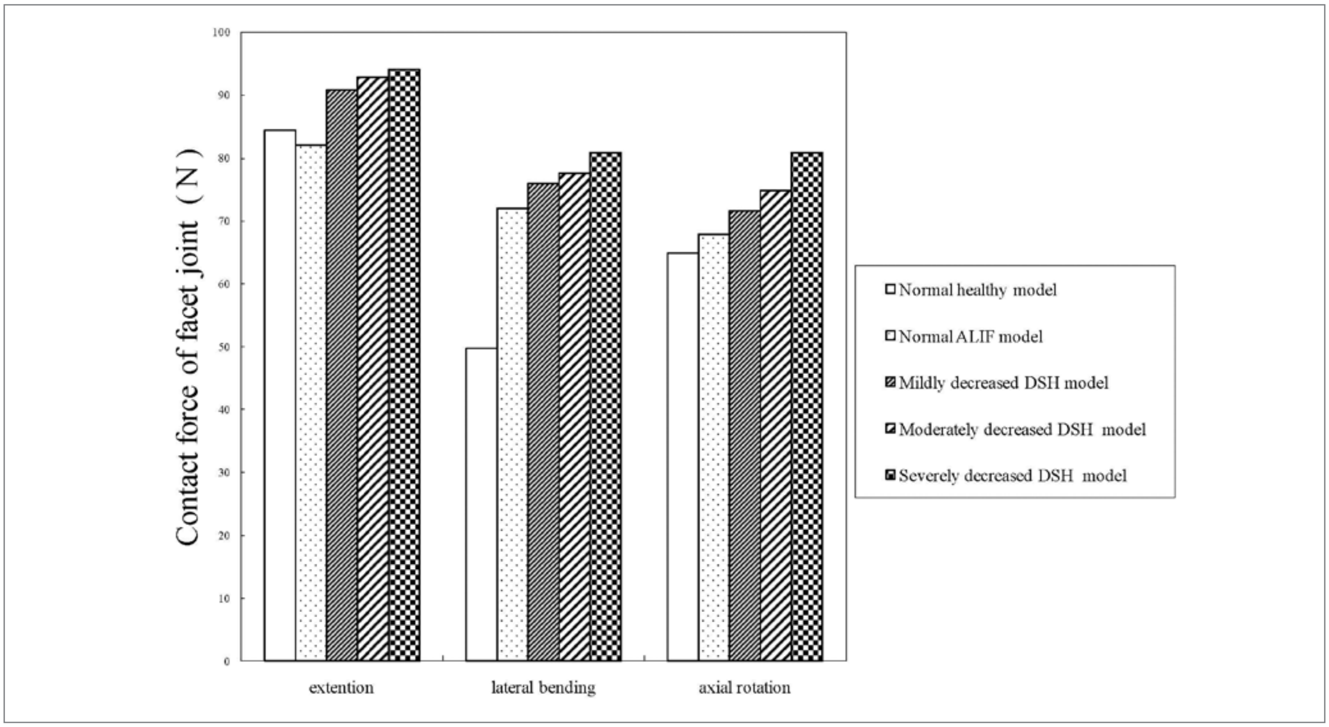

Figure 5: Contact forces of facet joints in different loading directions and models.

changes, especially at levels cranial to the fused segment. Many studies (17,2,6,27) have reported the effect of ALIF on the adjacent segments, suggesting that hypermobility, intradiscal pressures, tresca stress are increased within adjacent levels. In the present study, intradiscal pressures of L3-4 in normal ALIF model increase 82.6%, 37.0%, 42.9%, and 26.7%, the intersegmental rotation increases 23.5%, 26.5%, 9.8%, and 15.0%, and the tresca stress increase 213.9%, 84.8%, 61.7%, and 201% in flexion, extention, lateral bending, and axial rotation respectively, compared with the normal healthy model. These results are consistent with the previous studies.

In the present study, we assumed the fusion masses in all ALIF models have the same material properties, with the same young module and Poisson ratio. Although the bone graft have the different geometry, they have the same stiffness. Subsequently, they may have the same influence on the adjacent segments. However, the values of intradiscal pressure, intersegmental rotation and the tresca stress increase in three ALIF models with decreased DSH, when compared to the normal ALIF model. In addition, the values of three parameters increase gradually, with the decrease of DSH. Compare the severely decreased DSH model to normal ALIF model, the intradiscal pressure increase 23.8%, 16.2%, 33.5% and 42.1 %, intersegmental rotation increase 12.7 %, 30.1%, 8.9% and 10.4 %, and tresca stress increase 16.3%, 5.9%, 13.6% and 19.6% in flexion, extention, lateral bending and axial rotation respectively. Although some difference between models are small, we can confirm the trend that with the decrease of DSH, the influence of ALIF on the adjacent disc become severe gradually.

While creating three different DSH ALIF models from normal ALIF model, we found the decreasing of DSH was accompanied with the decreasing of segmental lordosis at fused segments, for the reason of the normal and intact posterior facet joints, which may prevent the decrease of posterior elements. In the present study, from normal ALIF model to mildly, moderately and severely decreased DSH ALIF model, the segmental lordosis decreased 5°, 10°and 15°, respectively. Using biomechanical study on ProDisc-L implants, Gaffey JL (9) concluded there was significant correlation between implant height and segmental lordosis and an increasing implant height produced a significant increase in segmental lordosis ($P<0.05$). In the report of twenty-six patients undergone lumbar interbody fusion, Kim SB (10) confirmed a loss of segmental lordosis has significant correlation with decrease of DSH resulting from cage subsidence. Also, many authors suggest the decrease of segmental lordosis in lumbar spine, may lead to the increase of loading strain and adversely prompt the adjacent segmental degeneration (1,24,16). Subsequently, we attribute the increase of intradiscal pressure, intersegmental rotation and tresca stress in L3-4 in the three decreased DSH ALIF to the decreased segmental lordosis. The loss of segmental lordosis may change the stress conduction and mechanical status of lumbar fuction unit, affecting the adjacent segment.

Facet joints are the primary components resisting loadings, distributing loadings and guiding movements (11,21). Although shear forces can be resisted by both disc and facet joints, the disc's viscoelasticity causes slowly applied or constant shear loads to pass through the facet joints (21). In the present study, under the loading direction of extention, lateral bending and axial rotation, there is little difference in the values of intersegmental rotations between moderately decreased DSH model and severely decreased DSH model, which can be interpreted by the limitation of facet joints to the hypermotility of lumbar function unit (14).

At the same time, when the DSH and lordosis angle of fused segment decrease, the stress on the lumbar spine may be changed, leading to more strain on the posterior columns and the facet joints, and subsequently, the contact force of facet joint may increase. Umehara et al (24) used human cadaver spines and made a two-level instrumented posterior fixation with different sagittal alignments at L4–S1 and they suggest that the strain at the L3 lamina increased when lordosis was decreased in the instrumented segments. In addition, the similar study was performed by Oda et al (16), in which the effects of a kyphotic aligned fusion on the adjacent levels were investigated using sheep model. Their study indicated that a kyphotic aligned fusion may lead to degenerative changes of the facet joints at the cranial adjacent level. In the present study, the results are similar with the previous two studies. Compared the severely decreased DSH model to normal ALIF model, the contact forces of facet joints increase 12.0N, 9.0N and 13.0N in extention, lateral bending and axial rotation. The increase of contact force of facet joints, together with the increase of intersegmental rotation, may prompt the degeneration of facet joints at the adjacent segments.

Subsequently, we suggest that the decreased DSH, or the decreased segmental lordosis of fused segment may adversely affect the adjacent superior segment in ALIF, leading to an increase of intradiscal pressure, intersegmental rotation, tresca stress and contact force of facet joints. Some difference of parameters between models are small, but the trend of aggravated degeneration can be approved. Therefore, it is believed that care and attention should be given to introduce segmental lordosis and disc space height in the normal range, and for this purpose, it is recommended that an anterior cage with appropriate height and lordotic angle as well as posterior instrumentation be used in ALIF surgery to maintain the proper DSH and segmental lordosis.

Our study does have inherent limitations. The structure of the vertebral body was assumed as the isotropic and homogenous property and the bone graft was assumed to completely occupy the disc space. These may not be truly representative of the in vitro or clinical situation. Additionally, in the present study we study the influence of DSH of fused segments on the adjacent degeneration, using ALIF models. However, the results may be different if the study is performed using other models such as transforaminal lumbar interbody fusion (TLIF) and posterior lumbar interbody fusion (PLIF). To further clarify these effects, more studies would need to be performed in the future.

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