



Investigating the mechanical effect of the sagittal angle of the cervical facet joint on the cervical intervertebral disc

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Abstract

Background: Facet tropism is defined as the asymmetry between the left and right facet joints relative to the sagittal plane. Published clinical studies have found that facet tropism is associated with cervical disc herniation. However, the relationship between the facet orientation and the side of cervical disc herniation remains controversial. Therefore, this study used the finite-element technique to investigate the biomechanical effects of the sagittal angle of the cervical facet joints on the cervical intervertebral disc.

Objective: The biomechanical effects of the sagittal angle of the cervical facet joint on the cervical disc and facet joint were investigated using the finite-element technique.

Methods: The finite-element model was constructed using computed tomography scans of a 26-year-old female volunteer. First, a cervical model was constructed from C3 to C7. The model was verified using data from previously published studies. Second, the facet orientation at the C5–C6 level was altered to simulate different sagittal angles of cervical facet joints. Five models, F70, F80, F90, F100, and F110, were simulated with different facet joint orientations (70°, 80°, 90°, 100°, and 110° facet joint angles at the left side, respectively, and 90° facet joint angles at the right side) at the C5–C6 facet joints. In each model, annular fibres stress and facet cartilage pressure were studied under six pure moments and two combined moments.

Results: Comparing the stress of the annulus fibres in flexion combined with right axial rotation and in flexion combined with left axial rotation in the same model, no difference in the maximum stress of the annulus fibres was noted between these two different moments in the F90 model, whereas differences of 12.80%, 8.84%, 14.95% and 33.32% were noted in the F70, F80, F100 and F110 models, respectively. The same trend was observed when comparing the maximum stress of the annulus fibres in each model during left and right axial rotation. No differences in annular fibres stress and facet cartilage pressure were noted among the five models in flexion, extension, lateral bending, left axial rotation, and flexion combined with left axial rotation in this study. However, compared with the F70 model in flexion combined with right axial rotation, the annulus fibres stress of the F80, F90, F100, and F110 models increased by 5.53%, 13.03%, 35.04%, and 72.94%, respectively, and the

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pressure of the left facet joint of these models decreased by 5.65%, 12.10%, 18.41%, and 25.74%, respectively. The same trend was observed in the right axial moment.

Conclusion: Facet tropism leads to unbalanced stress distribution on the annulus fibres at the cervical intervertebral disc. The greater the sagittal angle of the facet joint, the greater the annular fibres stress on this side. We hypothesised that the side with the larger sagittal angle of the facet joint exhibits a greater risk of disc herniation.

Keywords

Sagittal angle of facet joint, cervical intervertebral disc, annulus fibres stress, finite-element analysis

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Introduction

Degenerative changes in the cervical spine pose a huge burden to a society based on health expenditures and exhibit significant socioeconomic impacts on the allocation of medical diagnosis and clinical management resources.^{1,2} Therefore, to prevent degenerative cervical spinal disease and choose the appropriate treatment method, it is important to identify factors that promote the degenerative process.

A triple-articular complex is composed of intervertebral discs and bilateral facet joints.³ It not only promotes spine mobility but also limits excessive movement, which is an important biomechanical function. Any abnormality in one joint will affect the others. The sagittal angle of the facet joint is the angle between the facet joint and the sagittal plane in a transverse plane. Facet tropism is defined as the asymmetry between the left and right facet joints relative to the sagittal plane. According to Xu's measurement method,⁴ the sagittal angle of the facet joint was measured on axial computed tomography (CT), and its cross-section was parallel to the lower endplate of the upper vertebral body^{5,6} (Figure 1). Numerous studies have demonstrated the association between facet tropism and disc herniation in the lumbar spine.^{7–10} Some studies have found that the smaller sagittal angles on one side, the greater the risk of disc herniation on this side.^{6,8} However, little is known about the association of facet tropism with cervical disc herniation and the relationship between the facet orientation and the side of cervical disc herniation. Although published clinical studies have found that facet tropism is associated with cervical disc herniation,^{5,11} whether cervical discs tend to herniate on the side with the larger sagittal angle of the facet joint or the side with the smaller sagittal angle remains controversial. Previous finite-element (FE) studies have only demonstrated that facet tropism is associated with cervical disc herniation; however, these studies have not investigated the increased risk of herniation on the side with the larger or smaller sagittal angle of the facet joint.¹² Our clinical study found that the cervical disc herniates

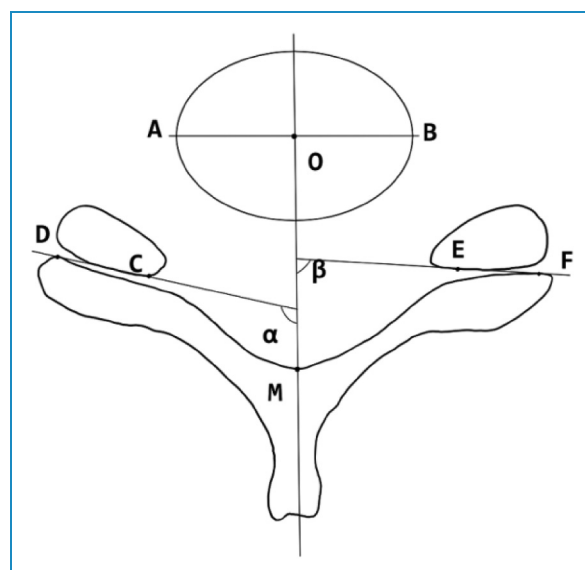


Figure 1. Illustration of the method used to measure the facet joint angles (superior view). The midsagittal line is drawn through the centre of the cervical disc (O, $AO = OB$) and the middle point of the base of the spinous process (M). The facet line was drawn between the anteromedial and posterolateral margins of each facet joint (C & D, E & F). The angle between the midsagittal line and the facet line represents the facet angle of each side (α = left facet angle; β = right facet angle).

towards the side of the larger sagittal angle of the facet joint.⁵ However, no biomechanical study was performed to explain these results. Therefore, we conducted this study to investigate the biomechanical effects of the sagittal angle of the cervical facet joints on the cervical intervertebral disc. We used a FE model of the cervical spine.

Materials and methods

We developed a three-dimensional (3D) FE model of the cervical spine based on CT data from a 26-year-old

healthy Asian female volunteer (160 cm, 52 kg). This study was approved by the Ethics Committee of the First Affiliated Hospital of Guangzhou University of Chinese Medicine. Participant provided written informed consent.

The CT data were obtained with a slice thickness of 0.75 mm by continuous scanning with a 64-slice spiral CT (SOMATOM Definition AS+, Siemens, Germany). The FE model was constructed using Mimics 19.0 (Materialize Inc., Leuven, Belgium), Geomagic Studio 2013 (Geomagic, Inc., Research Triangle Park, NC, USA) and SolidWorks 2014 (SolidWorks Corp., Dassault Systemes, Concord, MA, USA). The FE models were analysed using commercially available software (ABAQUS 2016, Dassault Systems Corporation, Velizy-Villacoublay Cedex, France).

Geometrical reconstruction of the cervical spine

Reference model of C3–C7

According to the methods of Mo et al.¹³ and Liu et al.,¹⁴ the CT data in DICOM format were imported into Mimics 19.0 software for the reconstruction of the C3 to C7 vertebrae. The five vertebrae at the C3–C7 levels were subjected to ‘Thresholding’, ‘Region Growing’, ‘Edit Masks’, and ‘Calculated 3D’ to reconstruct the preliminary 3D geometric model. Subsequently, the model was imported into Geomagic Studio software in STL format. ‘Grid Doctor’ was used to smooth the surface of the model, repair the holes and remove the spikes. Then, the model was fitted to an accurate surface using the probabilistic curvature method at the exact surface stage and was imported into SolidWorks 2014 software in STP format. The corresponding structures were established in SolidWorks 2014

software, including cortical bone, cancellous bone, endplate, intervertebral disc and paraspinal ligament. The thickness of the cortical bone and endplate was set to 0.5 mm.^{12,15} The intervertebral disc was subdivided into the annulus fibrosus and nucleus pulposus with a volume ratio of approximately 6:4.^{13,15,16} Paraspinal ligaments¹⁷ include the anterior longitudinal ligament (ALL), the posterior longitudinal ligament (PLL), the capsular ligament (CL), the ligamentum flavum (FL), and the interspinous supraspinous ligament (ISL). Here, 10, 8, 20, 5 and 10 connector elements were constructed for ALL, PLL, CL, FL and ISL, respectively, to show the characteristic of load-distribution behaviour in each ligament. These ligaments were modelled as truss elements that exclusively respond to tension. The transection area was 12 mm² for the ALL, 23 mm² for the PLL, 45 mm² for the CL, 14 mm² for the FL and 12 mm² for the ISL.^{12,13}

Then, ABAQUS 2016 software was used to set the properties of the cervical spine components. It is assumed that the properties of the material are linear, homogeneous and isotropic and have been described in previous studies as specified in Table 1.^{13–15,17,18} The annulus fibrosus was modelled as an annulus ground substance embedded with annulus fibres, which were positioned at an inclination of $\pm 25^\circ$ to $\pm 45^\circ$ from the transverse plane.^{14,17} Annulus fibres and ligaments were modelled as truss elements that exclusively respond to tension. Tied contact interfaces were used to ensure that the discs and ligaments were attached to the vertebra, preventing any relative movement during the simulation. Surface-based, finite-sliding contact with a friction coefficient of 0 was defined for facet joints.^{12,13} The convergence test indicated that the FE solution was accurate for the model with 165,638 nodes and 742,628 elements (Figure 2).

Table 1. Material properties and mesh types of the cervical finite-element model.

	Young's modulus (MPa)	Poisson ratio	Element type	Reference
Cortical bone	10,000	0.29	Tetrahedron (C3D4)	Liu et al. ¹⁴
Cancellous bone	100	0.29	Tetrahedron (C3D4)	Mo et al. ¹³
Endplate	1200	0.29	Tetrahedron (C3D4)	Mo et al. ¹³
Annulus ground substance	3.4	0.4	Hexahedron (C3D8R)	Mo et al. ¹³
Annulus fibre	110	0.45	Truss (T3D2, tension only)	Yuchi et al. ¹⁵
Nucleus pulposus	1	0.49	Tetrahedron (C3D4)	Wang et al. ¹⁸
Facet cartilage	10	0.4	Tetrahedron (C3D4)	Wang et al. ¹⁷
ALL/PLL/CL/FL/ISL	30/20/10/10/10	0.4	Truss (T3D2, tension only)	Mo et al. ¹³

ALL: anterior longitudinal ligament; PLL: posterior longitudinal ligament; CL: capsular ligament; FL: ligamentum flavum; ISL: interspinous and supraspinous ligament.

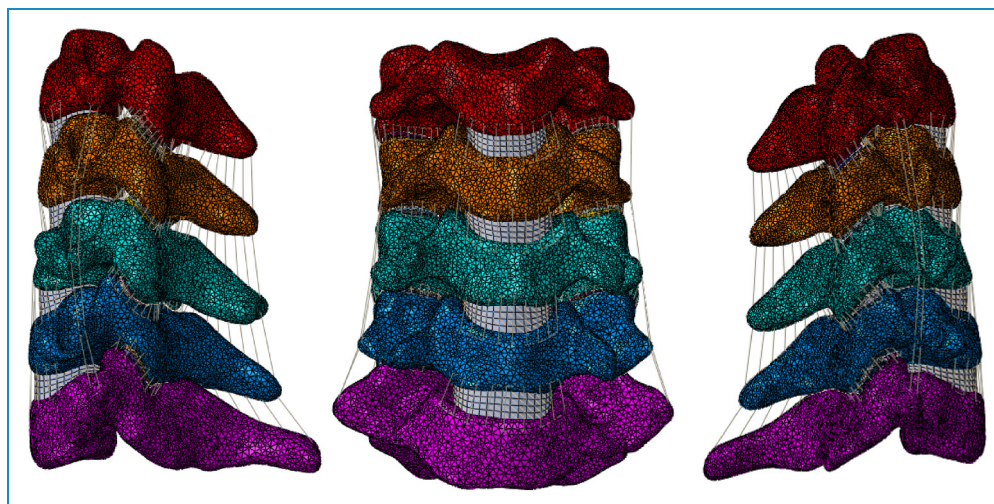


Figure 2. The three-dimensional finite-element model of C3-7.

Validation of the reference model

For model validation of C3-7, the inferior surface of the C7 vertebra was constrained. A vertical downwards pressure of 73.6 N^{13,17} was applied to the centre of the endplate on C3 to simulate the head weight. In addition to the head weight, 1.0 Nm moment loads were applied to the superior surface of the C3 vertebra to produce flexion, extension, lateral bending, and axial rotation, respectively. The range of motion (ROM) under all moments was obtained by measuring angular displacement and comparing it with the results of the in vitro study by Panjabi et al.¹⁹

The symmetrical C5-6 model and the facet tropism C5-6 model

After validation, the facet joint space at the C5–C6 level was filled with the same mask as the bone and treated as bony fusion in Mimics 19.0 software. Then, the ‘fused’ model was imported into SolidWorks 2014 software and ‘cut’ with a predetermined angle to simulate different sagittal angles of the facet joint without changing the other structures (Supplementary file). Five models, including F70, F80, F90, F100, and F110, were simulated with different joint orientations (70°, 80°, 90°, 100°, and 110° facet joint angles at the left side and 90° facet joint angle at the right side) at the C5-6 facet joints (Figure 3).

Validation and experimental conditions of the five new models of C5-6

The validation process of the new five models is roughly the same as that of the previous reference model. The inferior surface of the C6 vertebra was constrained. A vertical downwards pressure of 73.6 N was applied to the superior

endplate centre of C5 to simulate the head weight. A 1.0 Nm moment was applied to the superior surface of the C5 vertebra to produce flexion, extension, lateral bending, and axial rotation, respectively. The ROMs of five new models of C5-6 were recorded and compared with the results of the in vitro experiments by Panjabi et al.¹⁹ In addition, the annulus fibres stress and facet contact force were recorded under these experimental conditions.

In addition, the second test condition was to apply the combined moment of flexion and axial rotation under the head weight. We applied a pure moment of 1.5 Nm and a pure moment of 1.0 Nm simultaneously to simulate the combined motion of forward flexion and axial rotation of the human cervical spine and recorded the annulus fibres stress and facet contact force.

Result

Validation of the reference model of C3-7 and the new five models of C5-6

The ROM of each functional spinal unit in the reference model of C3-7 is shown in Figure 4(a), and these values are generally within the standard deviation of experimental data and literature.¹⁹ Similarly, the ROMs of the new five models of C5-6 are shown in Figure 4(b), which is consistent with the in vitro experimental results.¹⁹

Comparison of the annulus fibres stress in the new five models

The annulus fibres stress of the new five models of C5-6 is shown in Figure 5 under six pure moments and two combined moments. Comparing the stress of the annulus fibres in flexion combined with right axial rotation and in

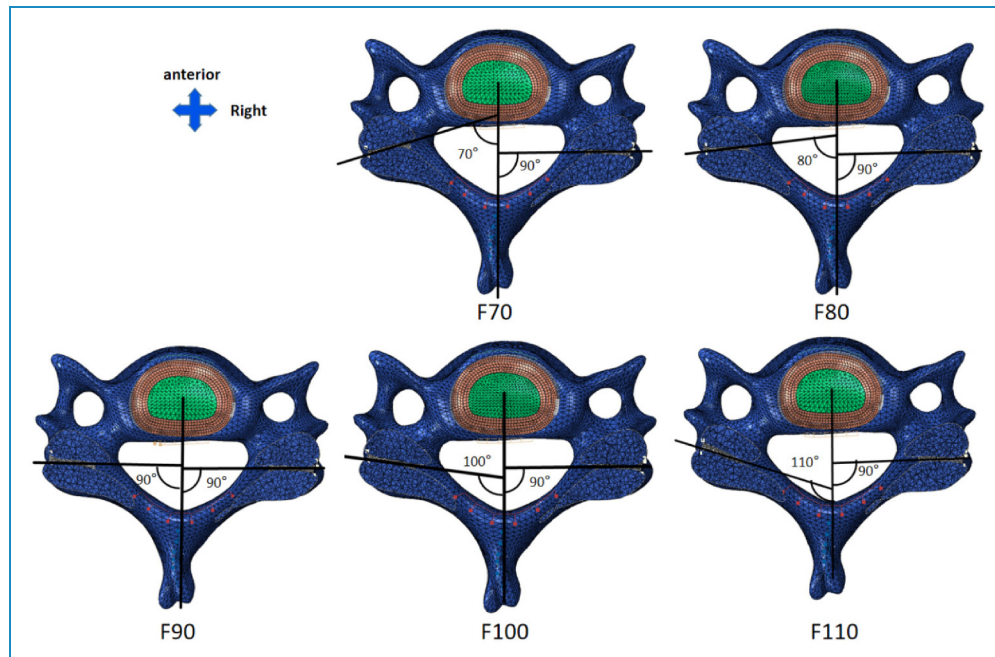


Figure 3. Axial cutting images (superior view) of five finite-element models of the facet joint on C5-6. In the F70 model, the left facet joint angle is 70° , and the right facet joint angle is 90° . Similarly, in the F80, F90, F100 and F110 models, the left facet joint angles are 80° , 90° , 100° , and 110° , respectively, whereas the right facet joint angle is 90° .

flexion combined with left axial rotation in the same model, we found no difference in the maximum stress of the annulus fibres between these two different moments in the F90 model. However, in the F100 and F110 models, the maximum stress on the left posterolateral annulus fibres under flexion combined with right axial rotation was larger than that on the right posterolateral annulus fibres under flexion combined with left axial rotation by 14.95% and 33.32%, respectively. This finding demonstrates that the more severe the facet tropism, the greater the difference in the stress of the annulus fibres. In the F70 and F80 models, the maximum stress on the right posterolateral annulus fibres under flexion combined with left axial rotation was larger than that on the left posterolateral annulus fibres under flexion combined with right axial rotation by 12.80% and 8.84%, respectively. A comparison of the stress of the annulus fibres in right axial rotation and left axial rotation also revealed the same trend.

The five models showed no difference in the annulus fibres stress under flexion, extension, lateral bending, left axial rotation and flexion combined with the left axial rotation moment. However, under right axial rotation and flexion combined with right axial rotation, the greater the left facet joint angle relative to the sagittal plane, the greater the stress on the annulus fibres on this side. Compared with the F70 model, the annulus fibres stress of the F80, F90, F100, and F110 models increased by 17.90%, 33.08%, 55.24%, and 79.87%, respectively, under the right axial rotation moment and 5.53%,

13.03%, 35.04%, and 72.94%, respectively, under flexion combined with the right axial rotation moment. Of note, the maximum stress of the annular fibres is concentrated on the left posterolateral under flexion combined with the right axial rotation moment and on the right posterolateral side under flexion combined with the left axial rotation moment (Figure 6).

Comparison of the pressure of facet joint in the new five models

The pressure of the facet joint in the new five models of C5-6 is shown in Figure 7 under six pure moments and two combined moments. There was no pressure on the left facet joint under flexion, left axial rotation, and flexion combined with the left axial rotation moment. The five models showed no difference on the left side of the facet joint pressure under extension and lateral bending moment, but under the right axial rotation and flexion combined with right axial rotation moment, the greater the left facet joint angle relative to the sagittal plane, the smaller the pressure on the left facet joint (Figure 8). Compared with the F70 model, the pressure of the left facet joint of the F80, F90, F100, and F110 models decreased by 3.56%, 10.84%, 13.79%, and 16.14%, respectively, under the right axial rotation moment and 5.65%, 12.10%, 18.41%, and 25.74%, respectively, under flexion combined with the right axial rotation moment.

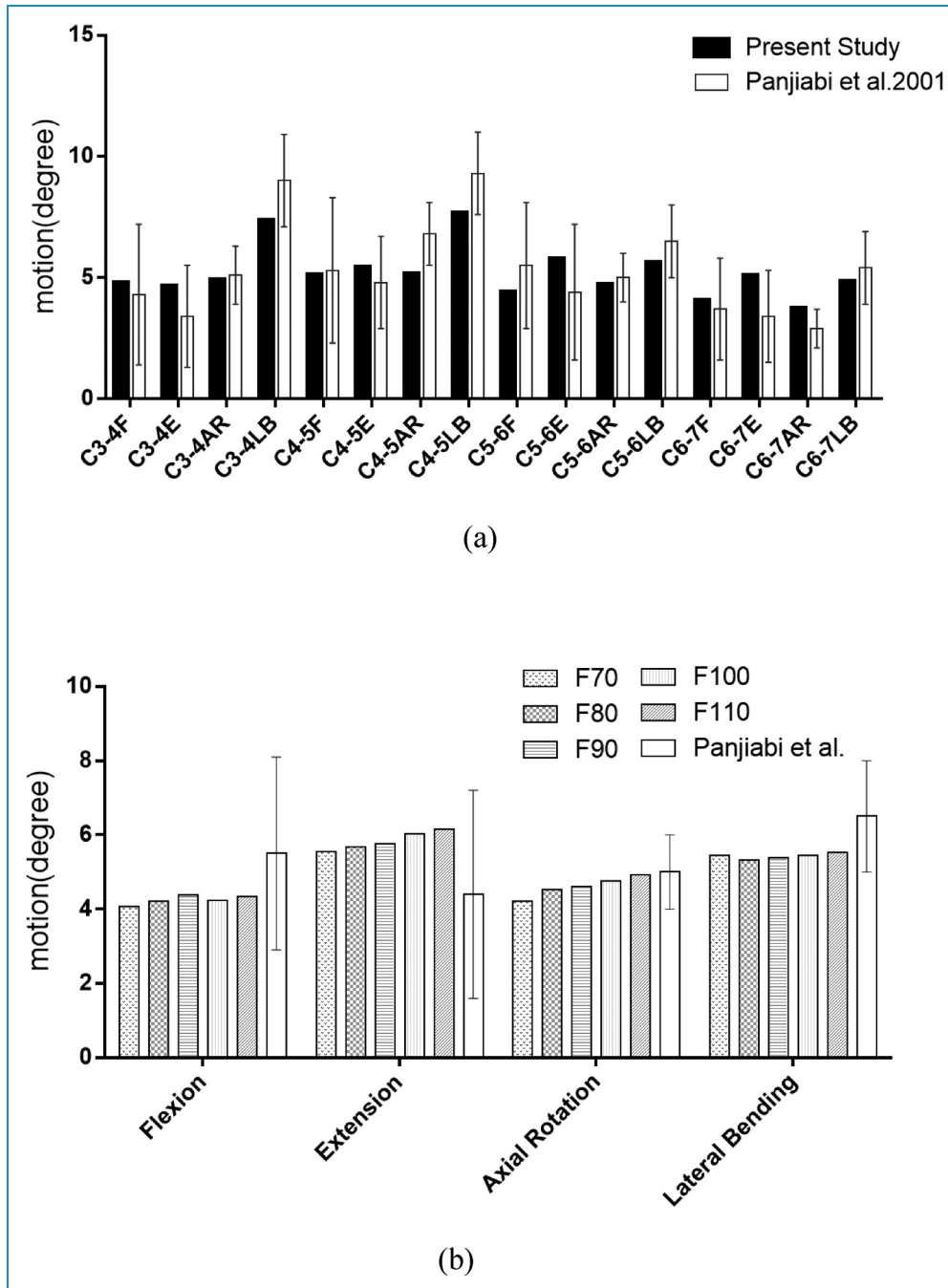


Figure 4. (a) Validation of the reference model of C3-7. The ROMs of all functional spinal units in the C3-7 models are generally within the standard deviation range of in vitro experimental data. (b) Validation of the five new models of C5-6. The ROMs of the new five models of C5-6 are similarly within the standard deviation range of in vitro experimental data. F: flexion; E: extension; AR: axial rotation; LB: lateral bending.

In addition, there was no pressure on the right facet joint under the flexion, right axial rotation, and flexion combined with the right axial rotation moment. The five models showed no difference in the pressure of the right facet joint under extension, lateral bending, the left axial rotation and flexion combined with the left axial rotation moment (Figure 8).

Discussion

In the lumbar spine, the facet joint is inclined almost vertically with respect to the horizontal plane, and the facet joint angle to the sagittal plane is approximately 45° .^{20,21} Such structural features allow flexion, extension or lateral bending of the lumbar spine but limit axial rotation. In

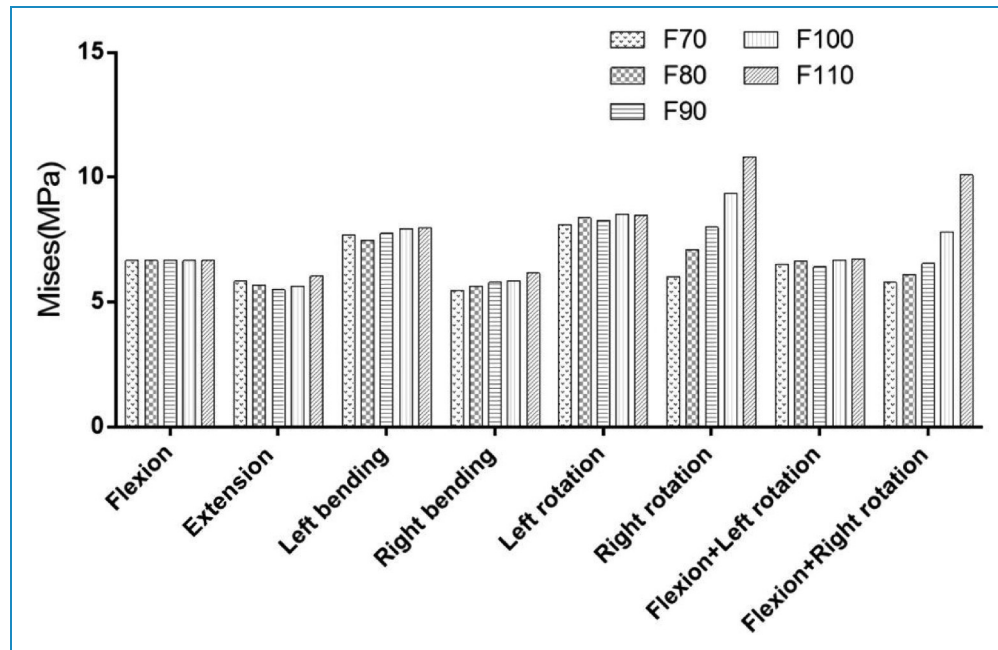


Figure 5. Comparison of the annulus fibres stress of C5–C6 among the five models under pure moments and combined moments. The annulus fibres stress differs under right axial rotation and flexion combined with right axial rotation.

contrast to the characteristics of the lumbar facet joints, the facet joint of the cervical spine is reported to be more complex.^{22,23} Regarding the facet joint angles to the sagittal plane, there are three types of cervical facet joint angles²²: the first type is noted when both facet joints are posteromedial oriented, that is, both facet joint angles are $<90^\circ$; the second is noted when both facet joints are posterolaterally oriented, that is, both facet joints angles are $>90^\circ$; the third type involves one side orienting posteromedially, one side orienting posterolaterally, that is, one side of the angle is $>90^\circ$ and one side is $<90^\circ$. Moreover, the angle of the cervical facet joint is approximately 45° with respect to the horizontal plane. Such structural features facilitate cervical movement, not only in flexion, extension, or lateral bending but also in axial rotation. Due to the different anatomical structures and movement characteristics of cervical and lumbar facet joints, the notion that the smaller sagittal angles on one side of the facet joint, the greater the risk of disc herniation on this side cannot be fully applied to cervical facet joints. Although some studies have shown that cervical facet tropism is associated with cervical disc herniation,^{11,24} minimal research has assessed which side of the cervical disc is at higher risk. Our clinical study found that the cervical disc herniates towards the side of the larger facet angle to the sagittal plane.⁵ However, no biomechanical study has been performed to explain these results. Therefore, this study used the FE technique to investigate the biomechanical effects of the sagittal angle of the cervical facet joints on the cervical intervertebral disc.

Interestingly, the results of this study showed that in right axial rotation or flexion combined with right axial rotation, the stress of the left posterolateral annulus fibres increased with an increasing sagittal angle of the left facet joint, whereas the pressure of the left facet joint cartilage decreased gradually. We hypothesised that this finding is because the larger sagittal angle of the facet joint poses less resistance to contralateral rotational motion. Thus, in contralateral rotation, facet cartilage with a larger facet joint sagittal angle is subjected to less pressure, whereas the ipsilateral disc is subjected to greater annulus fibres stress. The results of this study support our hypothesis. Previous studies suggested that the increased stress of the annulus fibres could be a predisposing factor for the development of disc degeneration.^{25,26} The increased loading on the annular fibres could cause microinjury to the annular fibre, and the accumulation effect of this repetitive microinjury could subsequently result in accelerating degeneration of the disc and disrupting the annular fibre.^{27,28} An animal experiment by Harvey-Burgess and Gregory²⁶ provides a proposed mechanism for the accelerated herniation progression. Specifically, axial rotation damages the annular fibre. With a damaged annular fibre, clefts will form more easily, allowing intervertebral disc herniation to progress more easily and subsequently more quickly when torsion is combined with flexion. Therefore, it is reasonable to assume that the greater the sagittal angle of the facet joint, the greater the risk of disc herniation on this side, especially when facet tropism causes abnormal stress concentration. Our hypothesis is similar to the hypothesis mentioned in the literature

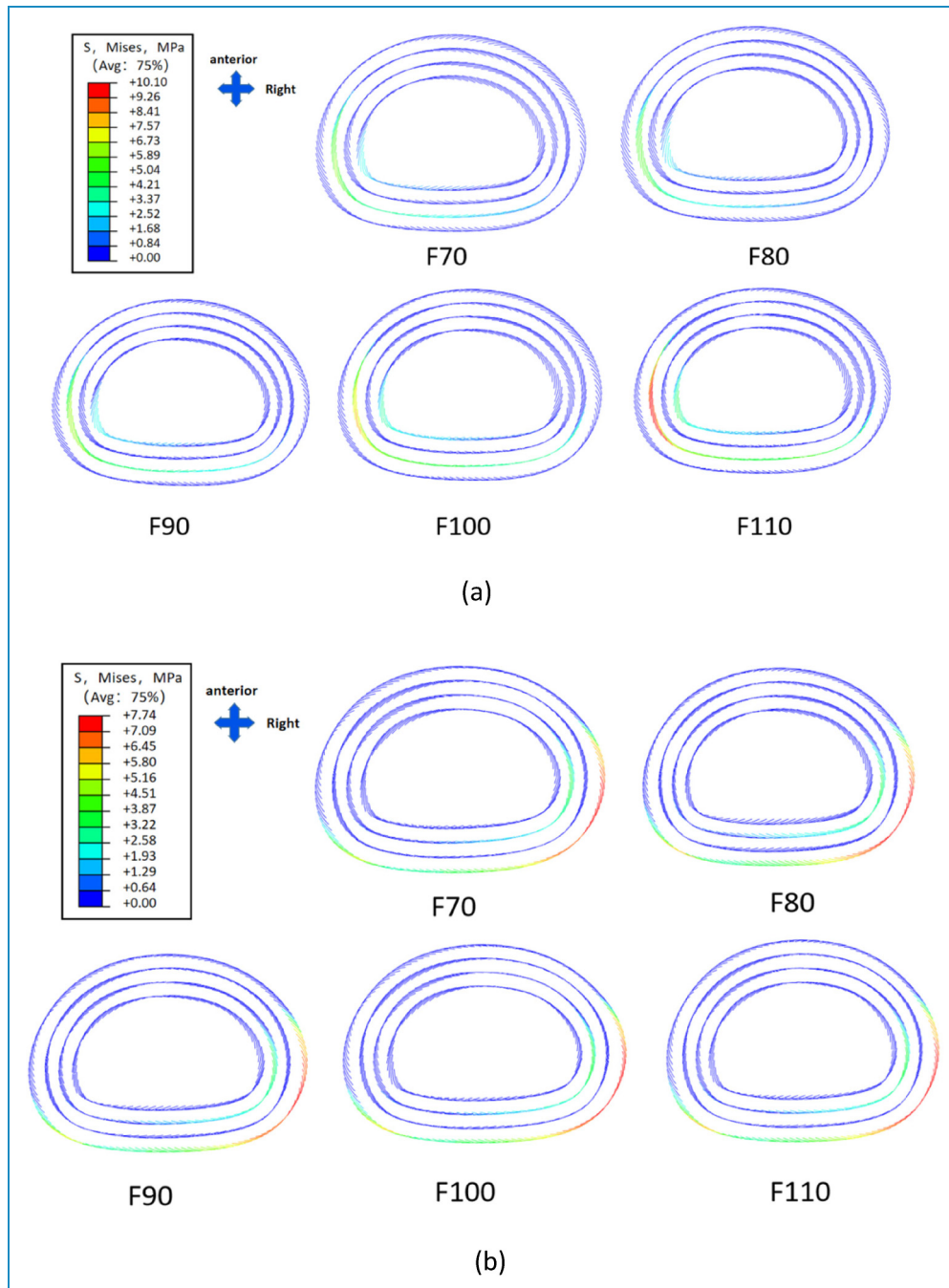


Figure 6. (a) Distribution of annulus fibres stress under flexion combined with right axial rotation in the five models (superior view). (b) Stress distribution for the annulus fibres stress under flexion combined with left axial rotation in the five models (superior view).

by Rong et al.²² When the facet is posterolaterally oriented, that is, the greater the sagittal angle of the facet, the resistance to rotation decreases, making the cervical spine more prone to rotation but increasing the likelihood of disc herniation.

In the previous section, we compared the changes of different models under the same moment. Then, we compared the stress changes of the annulus fibres in flexion combined with right axial rotation and in flexion combined with left

axial rotation in the same model. It was found that cervical facet tropism resulted in imbalanced stress distribution of the annulus fibres at the intervertebral disc. In addition, the more severe the facet tropism, the more serious the imbalanced stress distribution. The same trend was observed when comparing the maximum stress of the annulus fibres in each model during left and right axial rotation. The results were consistent with the results of previous

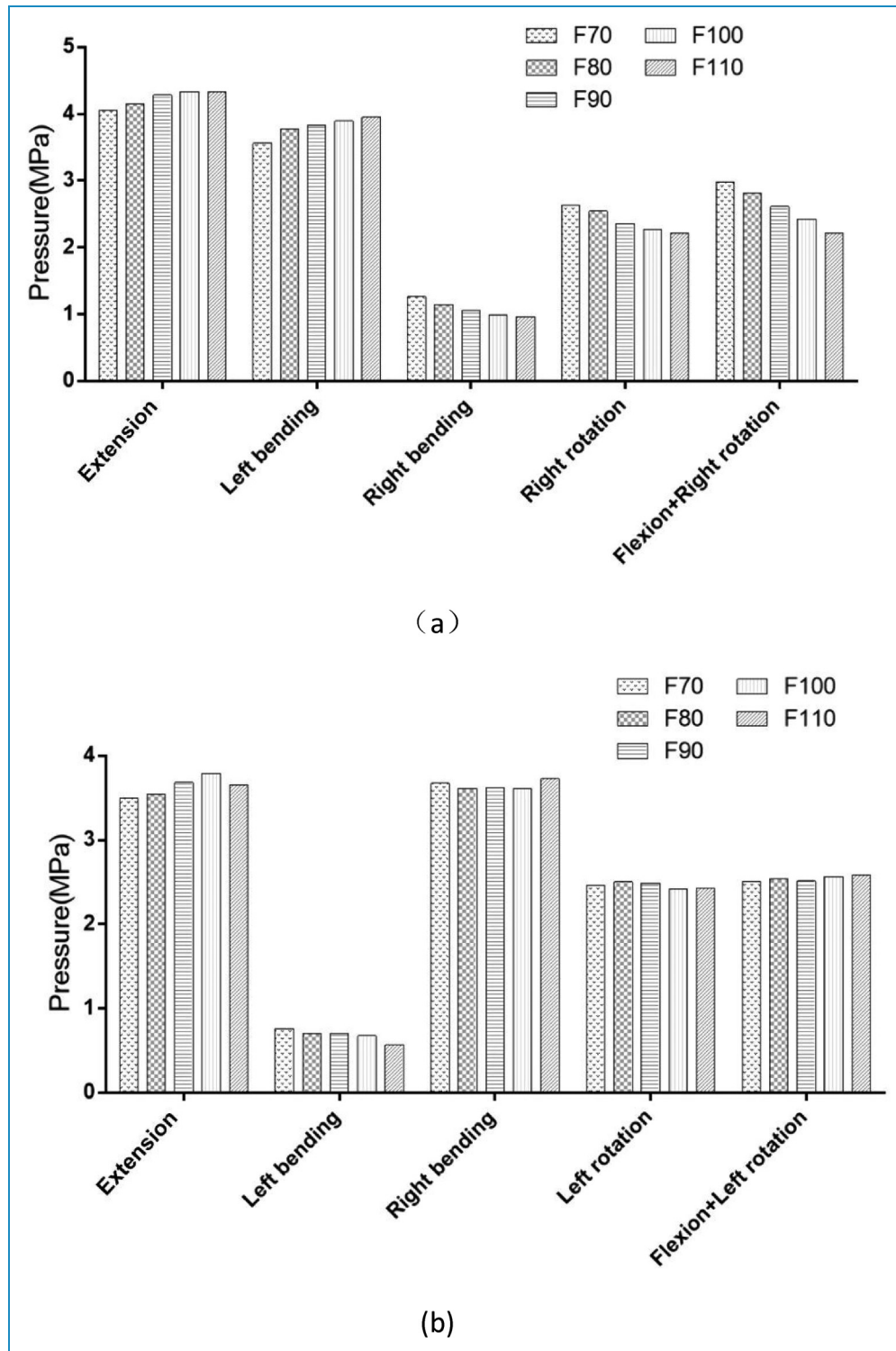


Figure 7. (a) Comparison of the facet joint contact pressure (left side) at the C5-6 segment in the five models. The pressure of the facet joint differs under right axial rotation and flexion combined with right axial rotation. (b) Comparison of the facet joint contact pressure (right side) at the C5-6 segment in the five models. No difference in facet joint pressure is noted among the five models.

studies on facet tropism.^{12,29} However, in contrast to previous studies,¹² this study only altered the sagittal angle of one side facet joint in different models, and the other

structures remained unchanged. Previous studies altered the sagittal angle of bilateral facet joints. In addition, whether the other structures were consistent was not

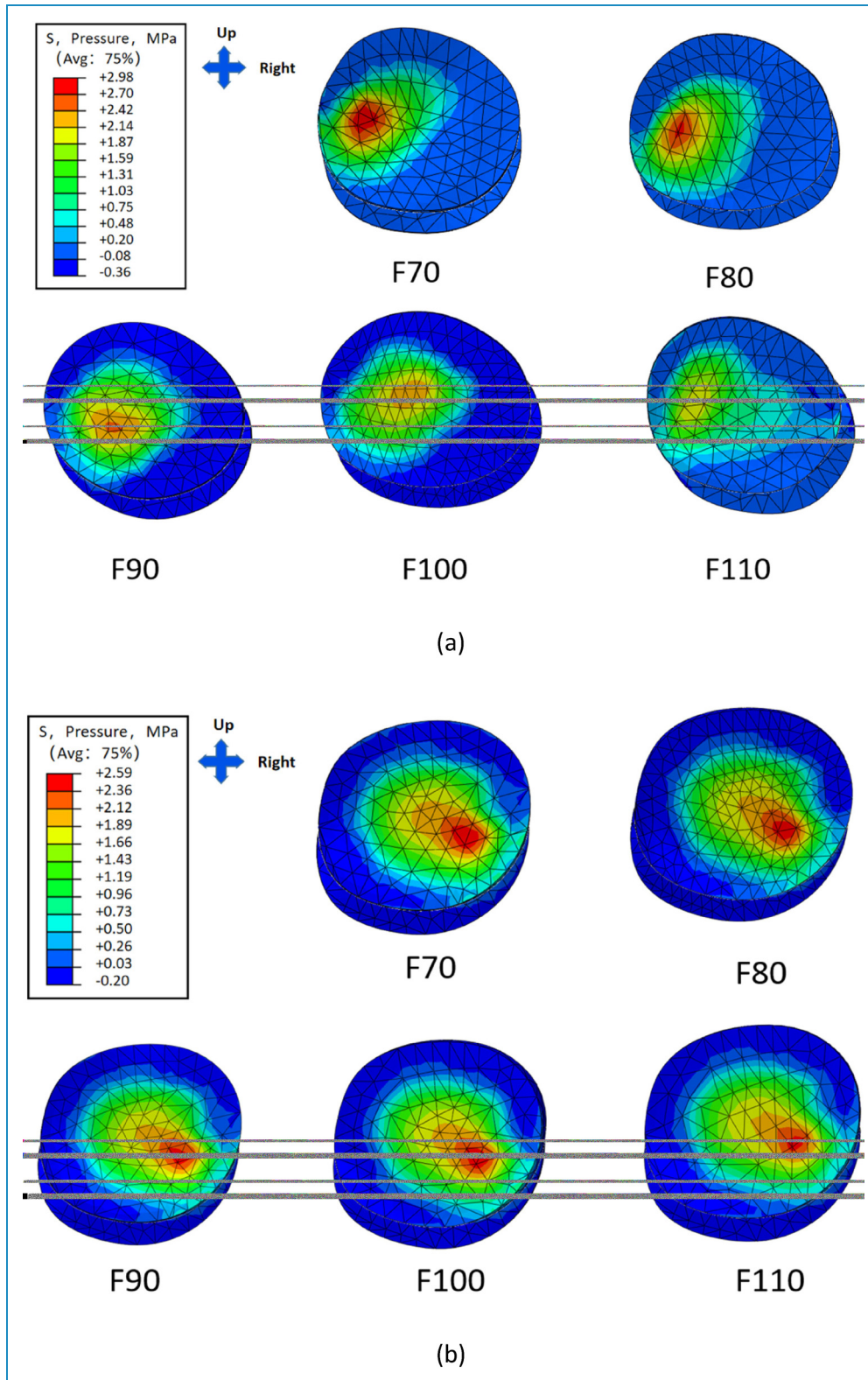


Figure 8. (a) Pressure distribution for the left facet joint under flexion combined with right axial rotation in the five models (posterior view). The maximum pressure of the left facet joint in the F110 model is the lowest. (b) Stress distribution for the right facet joint under flexion combined with left axial rotation in the five models (posterior view). The maximum stress and stress distribution of the right facet joint do not differ.

stated. Another difference is that we also found that the maximum stress of the annulus fibres is always concentrated on the posterolateral side of the larger facet joint sagittal angle in axial rotation or flexion combined with axial rotation. It is speculated that cervical disc herniation tends to occur on the side with the larger sagittal angle of the facet joint.

Based on the FE analysis of this study, the results suggest that patients with cervical facet tropism may not be suitable for artificial disc replacement (ADR). The purpose of ADR is to preserve cervical flexibility.³⁰ ADR rarely interferes with the cervical facet joint and thus cannot correct the imbalance of stress distribution caused by facet tropism. Previous biomechanical studies also found that the ROM of this segment increased and the stability decreased after ADR, which may exacerbate the abnormal distribution of stress.^{31,32} Furthermore, facet tropism was reported to cause progressive facet arthrosis in patients after disc replacement.³³ Therefore, patients with facet tropism seemed to be a contraindication for ADR. However, more studies of facet tropism as a contraindication of ADR surgery are needed. In addition, this study also has implications for cervical rotation manipulation in the treatment of cervical radiculopathy caused by cervical disc herniation. The key operation of cervical rotation manipulation in the treatment of cervical spondylotic radiculopathy is flexion and axial rotation to the healthy side.³⁴ However, according to the results of this study, this process can increase the stress on the posterolateral disc of the affected side and aggravate further disc herniation. This finding explains why some patients with cervical rotation manipulation experienced disc herniation aggravation^{35,36} and corroborate the hypothesis of a previous study.³⁷ Therefore, the impact of facet tropism on the cervical spine is of interest from clinical and public health perspectives.

Limitations

Some deficiencies in this study should be noted. First, the five FE models used for analysis were modified based on the reference model, and the five new models were inevitably different. However, to reduce the difference, we kept other structures consistent by using the same disc and the same right facet cartilage and keeping the volume and slope of the left facet cartilage consistent. Second, the movement of the facet was simulated as frictionless sliding of the upper and lower cartilage, and the ligament was simulated as linear, which did not completely represent the real situation. This simulation method is commonly used in FE analysis. In addition, we did not use an existing FE model with different angles of the cervical facet joint instead of constructing the model from a normal asymptomatic subject given the inevitable differences between the existing models of the different angles of the cervical

facet joint. These irrelevant variables easily affected the results. To exclude the influence of other unrelated factors, we investigated the effect of the sagittal angle of the cervical facet joints on the annulus fibres under ideal conditions using a normal young asymptomatic subject. However, the result we found only serves as a hypothesis because the result is based on an idealised FE model. Therefore, more clinical and animal studies are needed to confirm the relationship between the sagittal angle of cervical facet joints and cervical intervertebral discs.

Conclusion

In summary, this study demonstrated that facet tropism leads to unbalanced stress distribution on the annulus fibres at the cervical intervertebral disc. The greater the sagittal angle of the facet joint, the greater the annular fibres stress on this side. We hypothesised that the side with the larger sagittal angle of the facet joint exhibits a greater risk of disc herniation.

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Ethical approval: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All methods in this study were carried out in accordance with the provisions of the Declaration of Helsinki (as revised in 2013). This study was reviewed and approved by the Ethics Committee of The First Affiliated Hospital of Guangzhou University of Chinese Medicine (No. JY[2020]291). Informed consent was obtained from the volunteer and this consent was written.

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