

Finite element study on effect of follower load on intersegmental rotation, facet joint force and nucleus pressure of the cervical spine

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Abstract

Background: The follower load is used to simulate the physiological compressive load of human spine. These compressive loads can maintain cervical spine's mechanics stability and play a significant role in improving load-carrying capacity of the cervical spine. However, under different follower loads the biomechanical response of the cervical spine is unknown. So the aim of this study is to investigate the effect of follower load on biomechanics of the cervical spine.

Results: In this study, a three-dimensional nonlinear finite element (FE) model of the cervical spine (C3-C7) was built and validated. Using this FE model of the cervical spine, we evaluated the effect of different follower loads on intersegmental rotation, facet joint force, and nucleus pressure in the cervical spine. The results indicated that with the follower load increased, the intersegmental rotation of the cervical spine in extension decreased, but the intersegmental rotation in other postures increased. The follower load increased the facet joint forces in all postures. In lateral bending (LB), the facet joint forces were only generated in the ipsilateral facet joints. In axial rotation (AR), there was a large asymmetry in the facet joint forces, and this asymmetry worsened with the follower load increased. The nucleus pressure of each segment nonlinearly increased with the follower load increased in all postures.

Conclusion: An comprehensive analysis in intersegmental rotation, facet joint force and nucleus pressure under different follower loads can provide us a deeper understanding of the follower load in the human spine.

Background

The human cervical spine is capable of bearing substantial follower compressive loads *in vivo* [1]. These compressive loads can maintain human cervical spine's mechanical stability and play an important role in improving load-carrying capacity of the cervical spine [1]. However, previous research has been reported that the cervical spine cadaver specimens collapsed under a very low levels of load, much lower than the physiological compressive load *in vivo* [2]. Therefore, it appears that the traditional *in vitro* experimental methods rarely include the compressive loads similar to those experienced *in vivo*, especially in the studies of multi-level cervical spine [3].

Follower load has been used to simulate the physiological compressive load of the human spine and most previous research has reported that its value in the cervical spine was usually beyond 100 N [4-7]. To quantify biomechanical behavior of the human spine under the follower load, researchers have performed various *in vitro* experiments and finite element (FE) studies by applying compressive loads [3,6,8-15]. However, most experimental studies to date have focused on the lumbar spine [8-11], with only a few experimental studies evaluating the effect of the compressive load on the cervical spine [3,6,12-15]. For example, Cripton et al. reported that different application method of compressive load may affect the postures and motions of the cervical spine [12]. Ng et al. investigated the biomechanical effect of orientation angles and preload magnitudes on the cervical spine at C5-C6 level [3]. Kevin et al.

applied a follower load on C3-C7 segment of the cervical spine specimen using a robot test device, and used this robot test device to investigate the influence of follower load on the moment-rotation parameters and intradiscal pressure of the cervical spine [13]. In addition, under single magnitude follower load some researchers have conducted biomechanical testing of cervical spine specimens [14–15]. Nevertheless, there are a lack of FE studies that predict biomechanics response of C3-C7 segment of the cervical spine under physiologic compressive loads.

Regarding facet joint force, some in vitro experiments have demonstrated that the facet joints transmit loads through the spinal column and limit the movement of the vertebral body, especially during axial rotation (AR) and extension [16–18]. In addition, Goel et al. examined the distribution characteristics of facet joint forces and also reported that the application of a preload reduced the load in certain spinal components [19]. Ung-Kyu et al. studied the changes in adjacent segmental facet joint force after cervical facet joint replacement and found that the facet joint force increased after artificial joint replacement [20]. Kuo et al. analyzed the contact behavior of the facet joints and changes in nucleus pressure associated with different postures [21]. It is worth noting that Du et al. have studied in detail the effect of the follower load on facet joint forces in the lumbar spine [22]. However, the influence of different compressive preloads on facet joint forces in the cervical spine has not been previously examined.

Much of the previous researches of pressure into discs of have focused on the lumbar spine and these studies have shown that nucleus pressure increase with the increase of compressive loads and are related to the grade of intervertebral disc degeneration [11,23–24]. The studies of examining the influence of the follower load on the nucleus pressure in the thoracic spine are also more and more attractive to the researchers [25–26]. In addition, some researchers have evaluated the effect of compressive load on the nucleus pressure of cervical spine by utilizing in vitro experiments [13,15]. Thus far, Hattori et al. has been the only team to perform an in vivo study investigating nucleus pressure of the cervical spine [27]. Due to technical barriers and ethical conflicts in vivo experimental studies., later most researchers have chosen to investigate nucleus pressure by utilizing in vitro experiments methods. However, to date few researchers have used FE models to determine the changes of nucleus pressure of the cervical spine under different follower load [15]. It is worth noting that the FE models is easier to modify the material properties of cervical spine and is more suitable for performing parameter analysis.

Accordingly, the purpose of this study is to determine the effect of the follower load on biomechanics of cervical spine. To do so, a three-dimensional nonlinear FE model of the C3-C7 segment of cervical spine was developed and validated. Using this FE model of the cervical spine, we evaluated the effect of various follower loads (0 N, 50 N, 100 N, 150 N) on intersegmental rotation, facet joint force, and nucleus pressure in cervical spine.

Results

Calibration and validation

The calibration processes are shown in Figs. 1 (a-c) and the validation results are shown in Figs. 2 (a-c), and Figs. 3 (a-d). The intersegmental rotation obtained by this finite element model were compared with the cadaver experiment data [40–44]. Figure 3 shows the intersegmental rotation in each posture of the almost all segments closely matched the cadaver experiment data, only the intersegmental rotation of the C3-C4 segment in lateral bending (LB) is lower than the cadaver experimental data. Therefore, the model was considered calibrated and validated, and can be used to study the biomechanics response of the cervical spine under different follower loads.

Intersegmental rotation

The intersegmental rotation of each segment generated under various follower loads with no postural moment applied are shown in Fig. 4 (a). No intersegmental rotations exceeded 2.5 degrees, and the maximum intersegmental rotation was observed in the C5-C6 segment for all follower load levels. The intersegmental rotation of all segments generated in different postures under various follower loads are shown in Figs. 4 (b-c). The intersegmental rotation of all segments decreased with increasing follower load when in extension, but increased with increasing follower load in all other postures.

Facet joint force

In different postures, the predicted facet joint forces of different segments when under various follower loads are shown in Figs. 5 (a-c). In flexion, some facet joints had no facet joint forces, but the facet joint forces also increased with follower load increased. In extension, the facet joint forces of the C3-C4 segment were higher than other segments, while the load transmitted through the facet joint at the C4-C5 segment was the smallest. At the same time, the facet joint forces increased with an increase in the follower load. The facet joint forces on the left and right sides were not significantly different.

During LB, a facet joint force was generated only in the ipsilateral facet joint. For example, during right bending a facet joint force was generated only in the right side facet joint, and during left bending a facet joint force was generated only in the left side facet joint. As shown in Fig. 5 (b), the contact force of the facet joints on the left and right sides were not significantly different. And the facet joint forces increased with the follower load increased in LB. However, as shown in Figs. 5 (c), there was a large asymmetry in facet joint forces during AR. For example, during right axial rotation the facet joint forces on the left side were much larger than the facet joint forces on the right side. Similarly, during left axial rotation the facet joint forces on the right side were much larger than the facet joint force on the left side. This asymmetry was even more obvious with higher follower loads. During AR, the facet joint force of the facet joints on both sides increased with an increase of the follower load.

Nucleus pressure

Figures 6 (a-c) showed the nucleus pressure of each segment in all postures under various follower loads. In different postures, the nucleus pressure of all segments nonlinearly increased as the follower load increased. The nucleus pressure was minimal during extension, while the nucleus pressure was the

largest during flexion. The nucleus pressure significantly increased as the follower load increased during LB and also during AR. And during LB or AR, the values of the nucleus pressure were not significantly different.

Discussion

A three-dimensional FE model of the cervical spine(C3-C7) was built and validated. Using this three-dimensional FE model of the cervical spine, we evaluated the influence of the follower load on intersegmental rotation, facet joint force, and nucleus pressure in the cervical spine.

With an increase on follower load, the intersegmental rotation of all segments increased when in flexion, and the intersegmental rotation of all segments decreased when in extension. This result is similar to a previous study by Ng et al., who found similar increases in intersegmental rotation during cervical flexion when applying 100 N and 150 N compressive preloads at C5-C6 segment [3]. Kevin et al. applied a 100 N follower load to cadaver specimens of the cervical spine using a robot tool and reported that the intersegmental rotation of C4-C5 segment and C5-C6 segment increased slightly in flexion, similar to the results in our study [13]., Barrey et al. investigated the changes of cervical spine intersegmental rotation in flexion under 50 N follower load and their findings were also in agreement with our results [15]. Additionally, Puttlitz et al. evaluated the relationship between the follower load and cervical spine kinetics and showed that the follower load slightly decreased intersegmental rotation of C4-C5 segment in extension, agreed with the results of this paper [14]. Pelker et al. [46] investigated the rotational stability, strength, and failure mechanisms in cervical spine and found the compression load seemed to be related to cervical spine stability. It is worth noting that Moroney et al. [47] measured 35 fresh adult cervical spine cadavers under 73.6 N follower compression load and found that the stiffness of the cervical motion segments increased in extension. So we guessed that the follower load maintained the cervical spines's stability by increasing the segments stiffness.

Current researches of the effect of follower load on segmental flexibility of cervical spine mainly focus on flexion-extension. That because in vitro experiments, absolute compression of a cervical spine segment is probably obtained during both flexion and extension, whereas the application of a follower load during LB and AR may lead to a combination of shear and compressive forces, inducing significant changes in kinematics of the cervical spine [48–49]. Therefore, the inclusion of LB and AR in our study make it difficult to directly compare the findings of the present study to previously published work.

In this study, the change characteristics of multi-segmental cervical facet joint forces when under physiological compressive load were studied, which. can be used as a supplement to the follower load research. After static analysis, different response values of the facet joint forces when under follower load were observed at different postures (Figs. 5 (a-c)). In flexion, the gap between the two articular cartilage will become larger, so most of the facet joints have no contact forces. An obvious increase in facet joint force due to a follower load while in an extension posture is observed in Fig. 5 (a). This increase may be due to the follower load causing the upper and lower facet cartilages to displace and

produce larger deformation. A similar explanation was given in a study of the facet joint force of the lumbar spine under the follower load [22]. In addition, under the follower load the facet joint forces only existed in the ipsilateral facet joints during LB and the facet joint forces demonstrated a large asymmetry during AR, which may be related to the physiological structure of the facet joints of the cervical spine.

Due to the biomechanics responses of facet joint are sensitive to loading conditions, boundary conditions, and measuring method, large differences in the results of experimental and finite element studies of cervical facet joints have been observed. For example, Ung-Kyu et al. tested 18 normal human cervical spine specimens under a 2 N m moment and 150 N compressive load [20], and the reported facet joint forces of the C67 segment from that study are similar to our results in extension and LB, but our reported joint forces are slightly greater during axial rotation. The reason for this difference may be partially due to some facet joint forces not being recognized as a result of the compressive load impact in the experimental study. In addition, Barrey et al. found that the facet joint force increased systematically when applying a compressive preload to cervical spine specimens [15]. Patwardhan et al. reported that the cervical spine's carrying capacity increased sharply under a follower compression load and the facet joint force also increased [1]. The above change trends of the facet joint forces are all in general agreement with the results of our study.

To our knowledge, only Hattori et al. has attempted to measure the nucleus pressure of the cervical spine using in vivo experiments method. They found that the nucleus pressure of a healthy intervertebral disc was more and more larger from the supine position to sitting position and the nucleus pressure in sitting position was approximately 1.5 times greater than in supine position. Therefore, the effect of increasing follower load can be considered to be similar to the effect of moving a person from supine to a sitting position.

Pospiech et al. explored the relationship between the muscle strength and pressure into disc and found that the muscle strength played a significant role in increasing nucleus pressure [50]. And the follower load is generated by the synergy of muscle tissue. That is to say, the application of a follower compressive load will cause nucleus pressure of the cervical spine increase and the above change trend is agreement with our result. At the same time, Pospiech et al. specifically investigated the nucleus pressure of C3-C4 and C5-C6 under muscle load, finding that their values showed an increase to 1.2 times and 2.7 times respectively. Our findings confirmed those of the previous literatures, with a significant increase in nucleus pressure at both the C3-C4 and C5-C6 intervertebral discs with application of the follower load. In addition, Kevin et al. tested twelve human cervical spine cadaver specimens using a robotic test device and found that the nucleus pressure of C4-C5 segment and C5-C6 increased by 4.6 times and 2.6 times respectively after applying a 100 N follower load [13]. These results are very similar to the results of our study. Barrey et al. evaluated the change trend of nucleus pressure in cervical spine under 50 N follower load and their findings also indicated that nucleus pressure increased with the application of a follower load [15]. Additionally, in our study the nucleus pressure varied nonlinearly as increasing follower load, which may be because nucleus pulposus and annulus ground were defined as incompressible hyper elastic materials.

Follower load application method may be different in experimental research and finite element research, even if the method of applying the follower load in different finite element model also may be different. So it is very difficult to take a comparison quantitatively with other researches. But, in this study the change trend of the intersegmental rotation, facet joint force, and nucleus pressure in the cervical spine under the follower load are very compatible with the above studies. In addition, measuring facet joint forces using in vivo techniques and experimental methods is difficult or even impractical. That may be because the facet cartilages of the cervical spine have a greater relative slip compare with the lumbar spine, and it is more difficult to obtain reliable and stable experiment measurement data. However, in this paper the FE method is used to analyze the change trend of cervical spine facet joint force under the follower load. At the same time, we can get the data that is difficult to get experimentally, this is the advantage of finite element calculation.

It is very important to emphasize the limitations of the FE model of the cervical spine in this study. First, the current cervical spine FE model was built on the basis of the geometric information of single individual cervical spine, and it can only be used to reflect change trends of the cervical spine mechanics response under different loads. Moreover, the ligaments of this cervical spine were simulated as unidimensional nonlinear connector elements and the model was unable to simulate the true geometry of the ligament, which can affect motion of the cervical spine. Finally, there were no muscles simulated in the current model. Although this limitation was mitigated by the application of the follower load technique, the follower load could not entirely replace the muscles, which might actually have more complex contributions to the spinal response.

Conclusion

Our results demonstrated that the follower load decreased the cervical spine intersegmental rotation in extension, while causing an increase in intersegmental rotation in other postures. The ability of the facet joints to transmit loads increased after the application of a follower load. That is to say, the facet joint force of each segment in all postures increased as an increase on follower load. During LB, the facet joint forces were only produced on the ipsilateral facet joints. There was a large asymmetry of the facet joint forces during AR, and this asymmetry was amplified when increasing the follower load. The nucleus pressure of each segment increased along with increases in the follower load in all postures, and the nucleus pressure increased nonlinearly as the follower compressive load increased. Overall, an analysis combining patterns of intersegmental rotation, facet joint force, and nucleus pressure can provide greater insight into the biomechanical response of the cervical spine under different follower loads.

Methods

Development of Model

A finite element model of the cervical spine (C5-C6) was previously developed by our research team [28]. The detailed steps for building a FE model were obtained from previous researches [22,28]. Briefly, based

on the above FE model of the cervical spine [28], a three dimensional FE model of the cervical spine (C3-C7) was developed using a series of computed tomography (CT) scans in 0.625 mm slices from a young male subject (Fig. 7).

A single vertebra includes cortical bone, cancellous bone, endplate and posterior elements. Intervertebral discs are composed of two parts, a nucleus pulposus (44%) and the surrounding annulus (56%) [29]. The surrounding annulus comprises reinforcing fibers and annulus ground. And the angles between fibers layers and endplate plane approximately $\pm 25^\circ$ [30]. The five groups of major vertebral ligaments include the posterior longitudinal ligament (PLL), the anterior longitudinal ligament (ALL), the ligamentum flavum (LF), capsular ligaments (CL), and interspinous ligaments (ISL). For each spinal segment the number of the elements for PLL, ALL, LF, CL, and ISL ligaments are 5, 5, 6, 16, and 5, respectively. The original gap between the facet articular surface is approximately 0.5 mm [31]. The distribution of facet cartilage thickness in each facet was in accordance with the previous findings [32–33].

The material properties of the different cervical spine tissues (Tables 1) were taken from the literature [28,34–35]. The facet cartilage and each part of the vertebra were defined as linear isotropic elastic material. The nucleus pulposus and annulus ground were simulated as incompressible hyper-elastic materials [35]. As specified by Shirazi-Adl et al. [36], the fibers were simulated as tension-only truss. The ligaments were simulated as connector elements with nonlinear properties and their nonlinear material properties were determined according to previous research [37]. The material properties and element types of each component of cervical spine model (C3-C7) are shown in Table 1.

Table 1. Material properties and element types used for components in the cervical spine model [28,34–35].

Component	Young's Modulus (MPa)	Poisson's ratio	Element type
Cortical	10000	0.3	C3D8R
Cancellous	450	0.29	C3D4
Endplate	500	0.4	C3D8R
Posterior element	3500	0.29	C3D4
Fibers	110	0.45	T3D2
Facet cartilage	10	0.4	C3D8R
Annulus ground	Mooney-Rivlin,C10=0.133,C01=0.033,D1=0.6	-	C3D8RH
Nucleus pulposus	Mooney-Rivlin,C10=0.12,C01=0.09,D1=0	-	C3D8RH
Ligaments			
ALL	Nonlinear	-	CONN3D2
PLL	Nonlinear	-	CONN3D2
LF	Nonlinear	-	CONN3D2
CL	Nonlinear	-	CONN3D2
ISL	Nonlinear	-	CONN3D2

Loading and boundary conditions

A moment of 1 N m was applied on the node coupled with the superior surface of C3 endplate, and then the different additional follower loads (0 N, 50 N, 100 N, 150 N) were applied to the finite element model. The magnitude of the follower load applied in this study was based on previous researches [5–7,45]. The follower load is a physiological compression load along the axis of the cervical spine, wherein the intermediate nodes of each endplate are coupled to the endplate surface and the connector units are built through these nodes. And then, the follower load was applied at each level through these connector units [23,38]. During the whole loading process, the inferior surface of the C7 endplate was always fixed in six directions.

Calibration and validation

The FE model was calibrated and validated before being used to calculate data. The calibration processes were implemented according to the method proposed by Nicole et al. [39]. The correction factors of the collagen fibers and ligaments were modified, and the intersegmental rotation of each segment under the action of moment load was calculated and compared with the experimental data from previous research to validate the finite element model [40–44]. All simulation works of calibration and validation were completed using a commercial finite element software (Abaqus 6.11; Dassault Systemes Simulia Corporation, Pennsylvania, USA).

Abbreviations

FE: Finite element; CT: Computed tomography; ALL: Anterior longitudinal ligament; PLL: Posterior longitudinal ligament; LF: Ligamentum flavum; CL: Capsular ligament; ISL: Interspinous ligament; LB: Lateral bending; AR: Axial rotation.

Declarations

Acknowledgements

Not applicable.

Authors' contributions

CXY and YCCX carried out the model development and simulation, data analysis and drafted the manuscript. DCF participated in the study design. DCF and MZJ participated in revising the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data used and analyzed during the current study are available from the corresponding author on a reasonable request.

Ethics approval and consent to participate

The subject in this study was a healthy people, and they did not receive any clinical examination. Thus, the ethics approval is not applicable. Every participate had signed a consent form before the experiment.

Consent for publication

All authors read and approved the final manuscript. They both signed written informed consent forms.

Competing interests

The authors declare that they have no conflict of interest.

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Figures

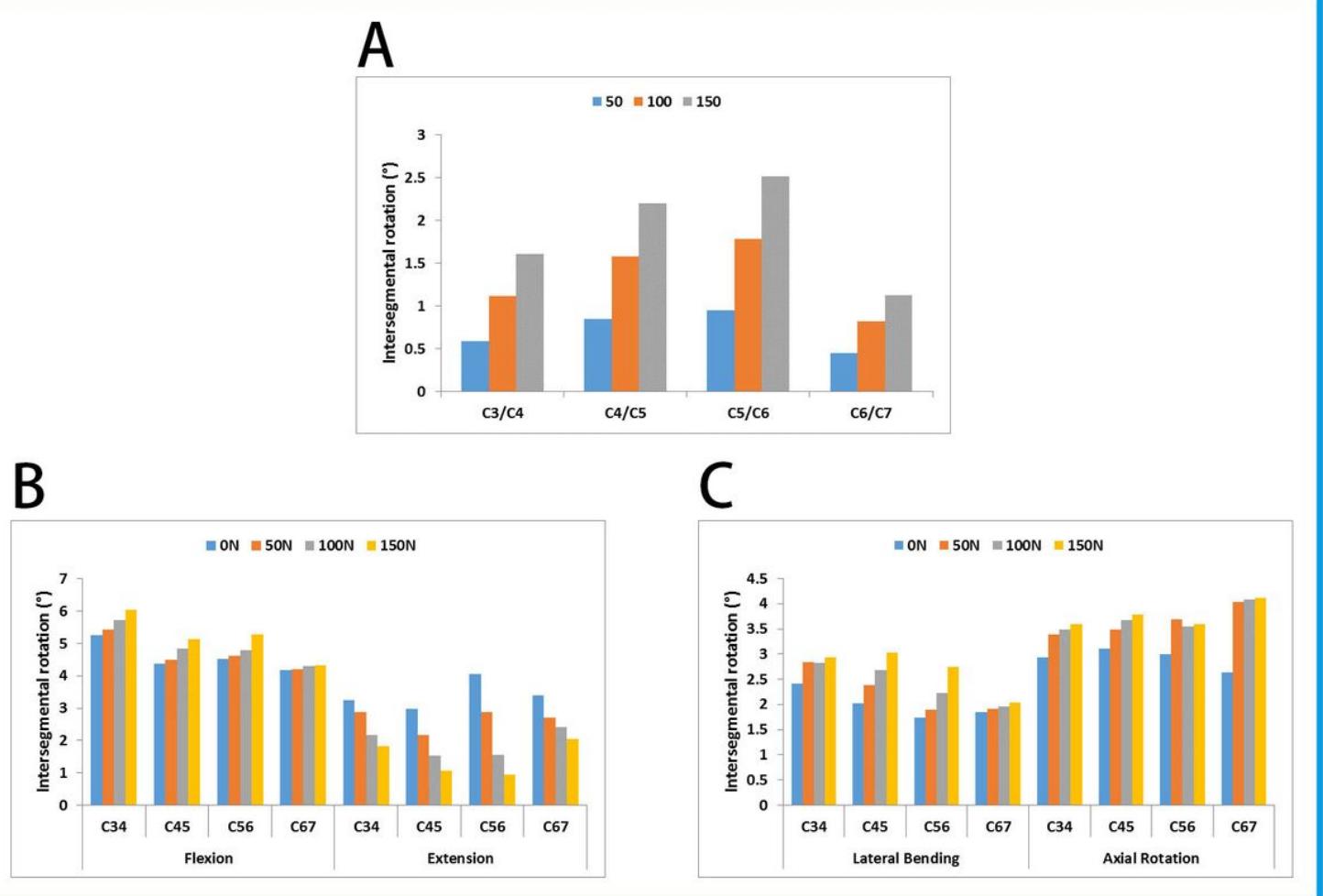


Figure 1

The effect of the follower load on the intersegmental rotation of the cervical spine. (a): The effect of the follower load on the intersegmental rotation of cervical spine (only under follower load). (b): The effect of the follower load on the intersegmental rotation of cervical spine (flexion-extension). (c): The effect of the follower load on the intersegmental rotation of cervical spine (lateral bending- axial rotation).

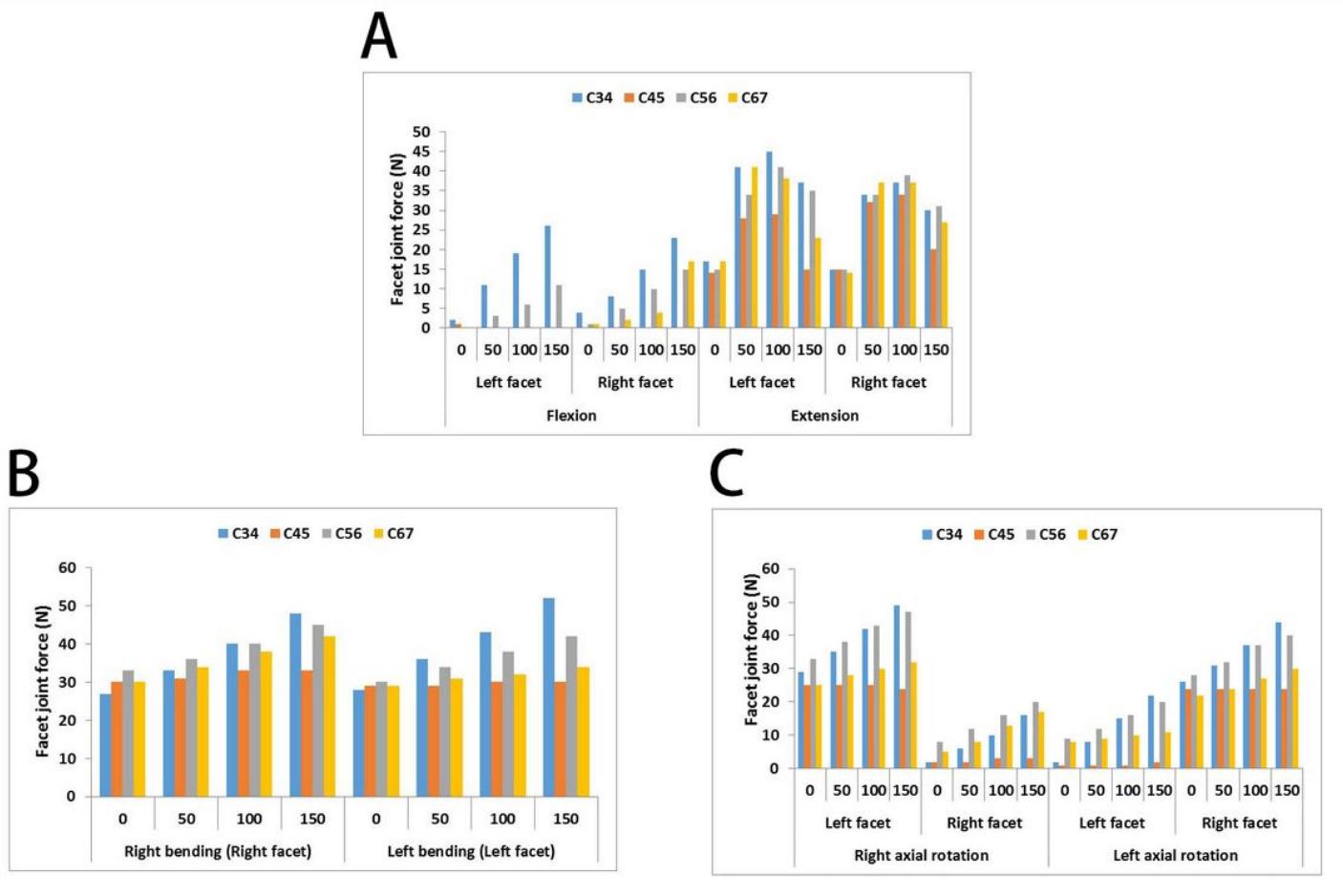


Figure 2

The effect of the follower load on the facet joint force of cervical spine in six directions. (a): The effect of the follower load on the facet joint force of cervical spine (flexion-extension). (b): The effect of the follower load on the facet joint force of cervical spine (lateral bending). (c): The effect of the follower load on the facet joint force of cervical spine (axial rotation).

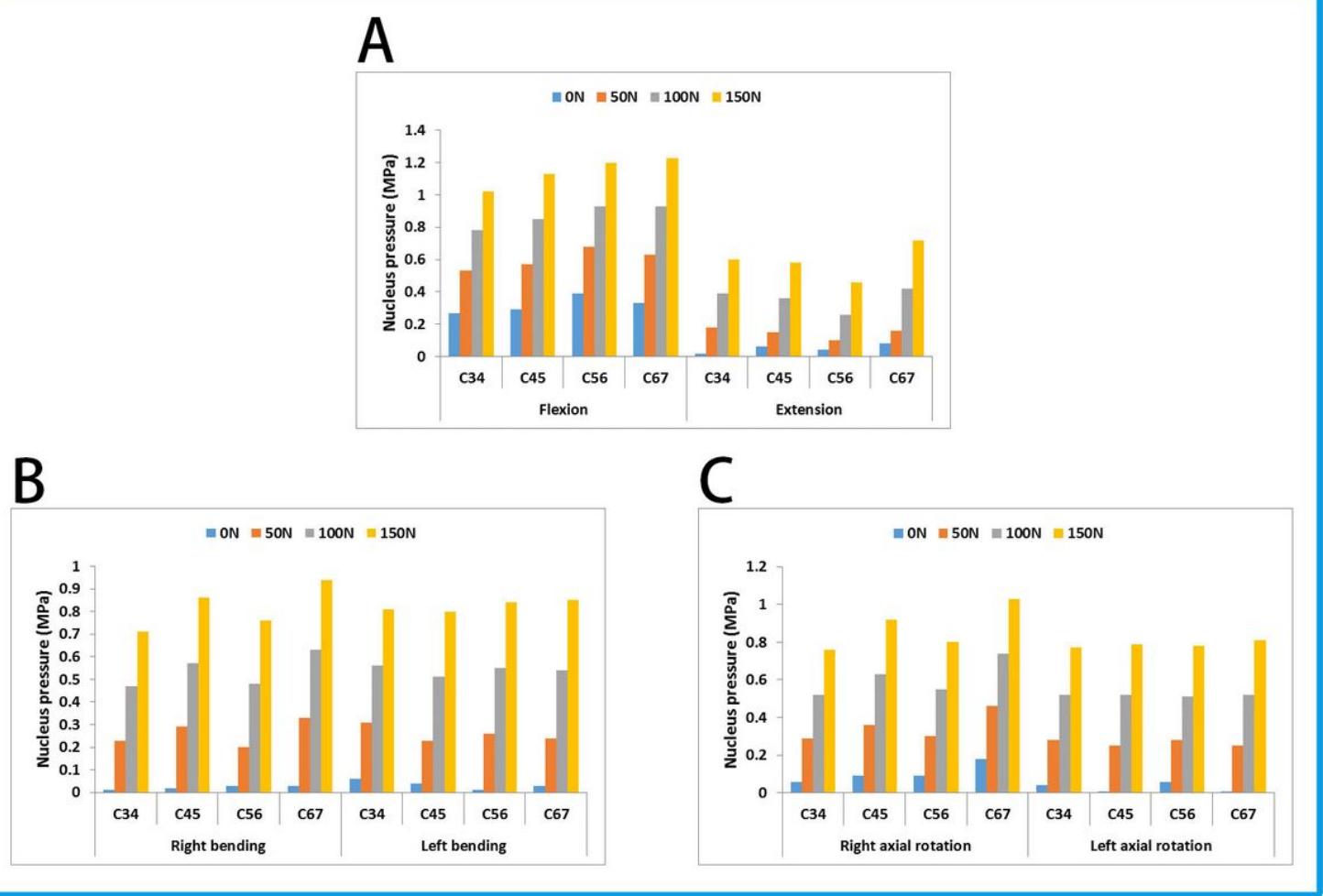


Figure 3

The effect of the follower load on the nucleus pressure of the cervical spine in six directions. (a): The effect of the follower load on the nucleus pressure of cervical spine (flexion-extension). (b): The effect of the follower load on the nucleus pressure of cervical spine (lateral bending). (c): The effect of the follower load on the nucleus pressure of cervical spine (axial rotation).

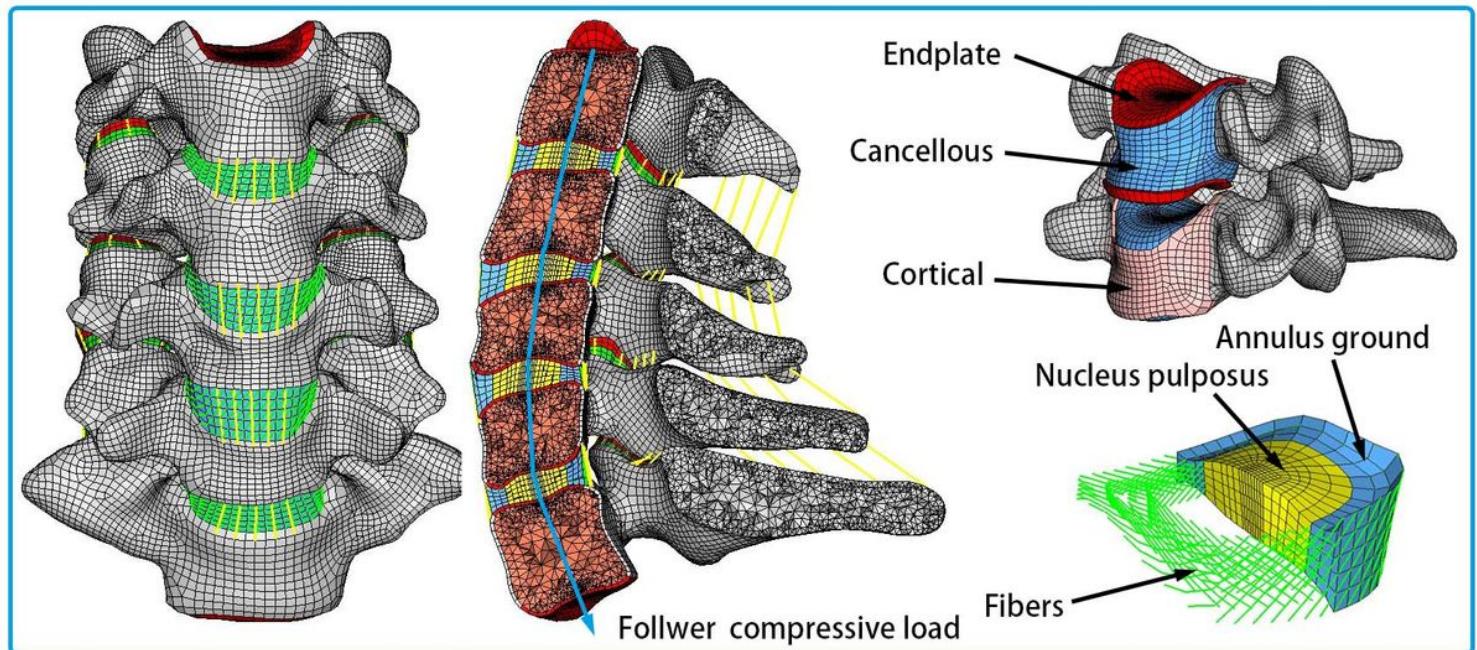


Figure 4

A three-dimensional nonlinear FE model of the cervical spine (C3-C7).