Biomechanical evaluation of graded ventral facetectomy simulating foraminoplasty of percutaneous endoscopic lumbar discectomy

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Abstract. – OBJECTIVE: To explore the lumbar spine biomechanics of graded ventral facetectomy and determine the appropriate extent of resection for foraminoplasty.

PATIENTS AND METHODS: We retrospectively measured several radiological parameters of superior articular process (SAP) and bony intervertebral foramen in computed tomography scans of 170 lumbar vertebral discs. The intact finite element (FE) spine of L2-sacrum was modified to simulate foraminoplasty with two typical graded ventral facetectomy methods (Method I: basal part resection of SAP; Method II: apical part resection of SAP) to explore the biomechanical effects under different physiological motions.

RESULTS: Examination of the radiological parameters of the bony intervertebral foramen indicated that they were generally narrower than the diameters of commercially available working cannulas. Some of these parameters showed gender differences. The biomechanical evaluation indicated that the range of motion increased gradually with the expansion of the resection extent, and the differences compared to the intact spine at the same level were greater in Method I than in Method II.

CONCLUSIONS: The appropriate ventral resection extent of the basal part of the SAP (Method I) was 4 mm, 3 mm, and 3 mm on the lateral view at L3-L4, L4-L5, and L5-S1, respectively. The appropriate ventral resection extent of the apical part of the SAP (Method II) were 10 mm, 6 mm and 6 mm on the lateral view at L3-L4, L4-L5, and L5-S1, respectively. Extensive resection of foraminoplasty may destabilize lumbar motion segments.

Key Words:
Percutaneous endoscopic lumbar discectomy, Foraminoplasty, Graded facetectomy, Superior articular process, Intervertebral foramen.

Introduction

A number of minimally invasive spinal techniques [e.g., arthroscopic microdiscectomy, selective endoscopic discectomy, and percutaneous endoscopic lumbar discectomy (PELD)] have been developed since percutaneous transforaminal discectomy was first introduced in 1975[1-5]. PELD is becoming one of the mainstream minimally invasive treatments for lumbar disc herniation due to its advantages over traditional open surgery, including the use of local anesthesia, small skin incision, little blood loss, and protection of posterior ligamentous, bony structure, and paravertebral muscles[6-9]. With the development of specialized instruments and techniques, such as foraminoplasty, the indications for PELD have expanded from non- or low-migrated disc herniations to high-grade migrations, lateral recess stenosis, and intervertebral foraminal stenosis[6,10].

Foraminoplasty, mainly applied to the lower spine, is a technique in which bone trephine reamers and high-speed drills are used to widen and restore the intervertebral foramen by undercutting the ventral part of the superior articular process (SAP), accompanied by ablation of the foraminal ligament to expose the anterior epidural space and its contents[11,12].

As it is safe and provides an adequate operation space, foraminoplasty can solve the problems associated with other methods, such as inadequate exposure, poor visualization, and inability to reach and grasp high-grade down migrated fragments. This procedure can also be used to treat lateral recess stenosis and intervertebral fo-

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raminal stenosis by resecting hypertrophic SAP and ossified ligamentum flavum, and by decompressing traversing and exiting nerves to alleviate radicular pain[6,8]. However, the lumbar facet joint plays an important role in maintaining spinal stability by spreading the load in extension and compression and protecting the discs from rotational forces and excessive shear[13]. Anatomical variation and asymmetry in the lumbar facet are not uncommon and may be related to disc degeneration and spondylolisthesis[14,15]. Moreover, extended resection of the facet joint may impact the kinematics of the motion segment, possibly leading to lumbar destabilization and additional stress in the remaining structures[16,17]. The underlying principle of foraminoplasty is that the facetectomy cannot touch the facet contact area to avoid instability of the spine[18]. However, due to the steep and long learning curve of PELD, different decompression concepts, anatomical variation, and hypertrophy of SAP, the extent of SAP resection differs among surgeons and sometimes over the joint surface, even with SAP completely removed in clinic[8].

Non-linear three-dimensional (3D) finite element (FE) analysis is an important method for biomechanical studies[19]. To assess the biomechanical impact of foraminoplasty and determine the appropriate extent of SAP resection, we performed a series of measurements on computed tomography (CT) scans of the bony intervertebral foramen according to the foraminoplasty working zone and projection length of the SAP, based on the concept of graded facetectomy in traditional surgery[13,20]. Therefore, we designed two methods of graded ventral facetectomy simulating foraminoplasty in an FE model, to explore the biomechanical effects of foraminoplasty on the lower lumbar spine.

Patients and Methods

Study Design and Patients

This study was approved by our Institutional Review Board. There has been no research studying the biomechanics of foraminoplasty of PELD till now. Besides, the indications for PELD have expanded extensively for different degrees of degeneration. Thus, we studied healthy people for this pioneering research to reduce the bias from different degeneration models after careful consideration. We retrospectively reviewed all lumbar disc CT scans from the electronic records archives of outpatients and inpatients in our hospital between January 2013 and December 2017. The CT data of non-degenerative lumbar discs and facet joints were included. Patients with scoliosis, spondylolisthesis, previous lumbar surgery, congenital malformation, spinal stenosis, or severe degenerative disc disease were excluded from the study. Finally, 170 patients (86 males, 84 females) ranging in age from 17 to 59 years (average age, 36.7 ± 10.1 years) were included in this study.

Radiographic Measurements

The radiological parameters were measured on CT with bone windows. The radiological variables related to the bony intervertebral foramen and projection length of SAP were defined as follows in Figure 1.

FE Model Investigation

Establishment and validation of an L2-sacrum FE model

A nonlinear 3D FE model of the L2-sacrum was constructed from CT scans with a thickness of 1 mm, obtained from a healthy 25-year-old Chinese man (body mass index = 21.4 kg/m^2) with no evidence of disc degeneration or facet osteoarthritic changes. The imaging data were imported into the Mimics 15.0 software program (Materialise, Leuven, Belgium) and transformed into a solid model. The vertebrae and pedicle were meshed using tetrahedral elements, and the intervertebral discs and endplates, while facet joints were meshed using hexahedral elements in Geomagic Studio (ver. 12.0; Geomagic, Morrisville, SC). The 3D FE model was then assembled (Pro/E 5.0; PTC, Needham, MA) with the L2-sacrum vertebral bodies, posterior elements, intervertebral discs [composed of 44% nucleus pulposus and 56% annulus fibrosus (AF)], endplates, and seven major ligaments. The material properties were determined from the literature (Table I)[21-23].

The elastic behavior of AF was simulated with eight annulus fiber layers modeled in a radial orientation[24] and the collagen fibers of the AF matrix were angled at 30° to 45° with respect to the horizontal plane and varied from the inner to the outer lamina of the AF. The surface-surface contact elements were used to simulate facet joints with a friction coefficient of 0.1[25]. To validate the model, range of motion (ROM) data for flexion (Flex), extension (Ext), left/right lateral bending (LLB/RLB), and left/right

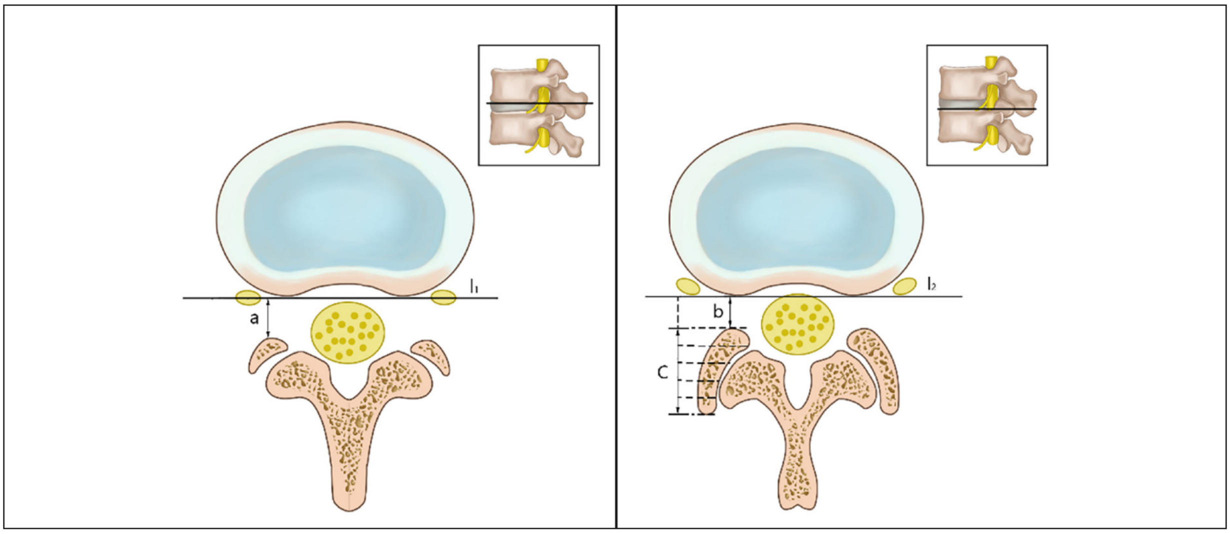

Figure 1. A schematic illustration of radiological measurements. **a**, (Distance A): the shortest distance between the horizon line (l1) of the vertebral posterior margin and the facet surface of the superior articular process at the plane of the inferior endplate of the superior vertebra. **b**, (Distance B): the shortest distance between the horizon line (l2) of the vertebral posterior margin and the facet surface of the superior articular process at the plane of the superior endplate of the inferior vertebra. **c**, (Distance C): the projection length of SAP on the vertical direction of l2 at the plane of the superior endplate of the inferior vertebra.

axial rotation (LAR/RAR) were compared to the results of a cadaveric biomechanical study[26], all were within one standard deviation of the reported average values, indicating that the intact FE model was viable.

Graded Ventral Facetectomy Model

To simulate the different resection extents of foraminoplasty in as much detail as possible, we designed two methods for graded ventral facetectomy of the left SAP at the L3-L4, L4-L5, and L5-S1 levels (Figure 2).

Method I (Ventral Basal Part Resection of SAP)

We divided the part of the left SAP above the plane of the superior endplate of the inferior vertebra into five regions parallel to the coronal plane; the projection lengths in the direction of Distance C, of each part at the plane of the superior endplate, were all equal. According to our anatomical classification of graded ventral facetectomy, the amount of bone removed in the FE model corresponded to the removal of 20%, 40%, 60%, 80%, and 100% of the left partial SAP from the ventral to the dorsal side.

Table I. Material properties in the present finite element models.

Component	Elastic modulus (MPa)	Cross-section (mm^2)	Poisson's ratio
Cortical bone of vertebral body	12,000		0.3
Cancellous bone of vertebral body	100		0.2
Pedicle	3,500		0.25
Facet joints	15		0.45
Endplate	24		0.25
Nuclear pulposus	1		0.499
Annulus fibrosus	4.2		0.45
Fibers of Annulus fibrosus	175	0.76	
Anterior longitudinal ligament	7.8	63.7	
Posterior longitudinal ligament	10	20	
Ligametum flavum	15	40	
Capsular ligaments	7.5	30	
Intertransverse ligaments	10	1.8	
Interspinous ligaments	10	40	
Supraspinous ligaments	8	30	

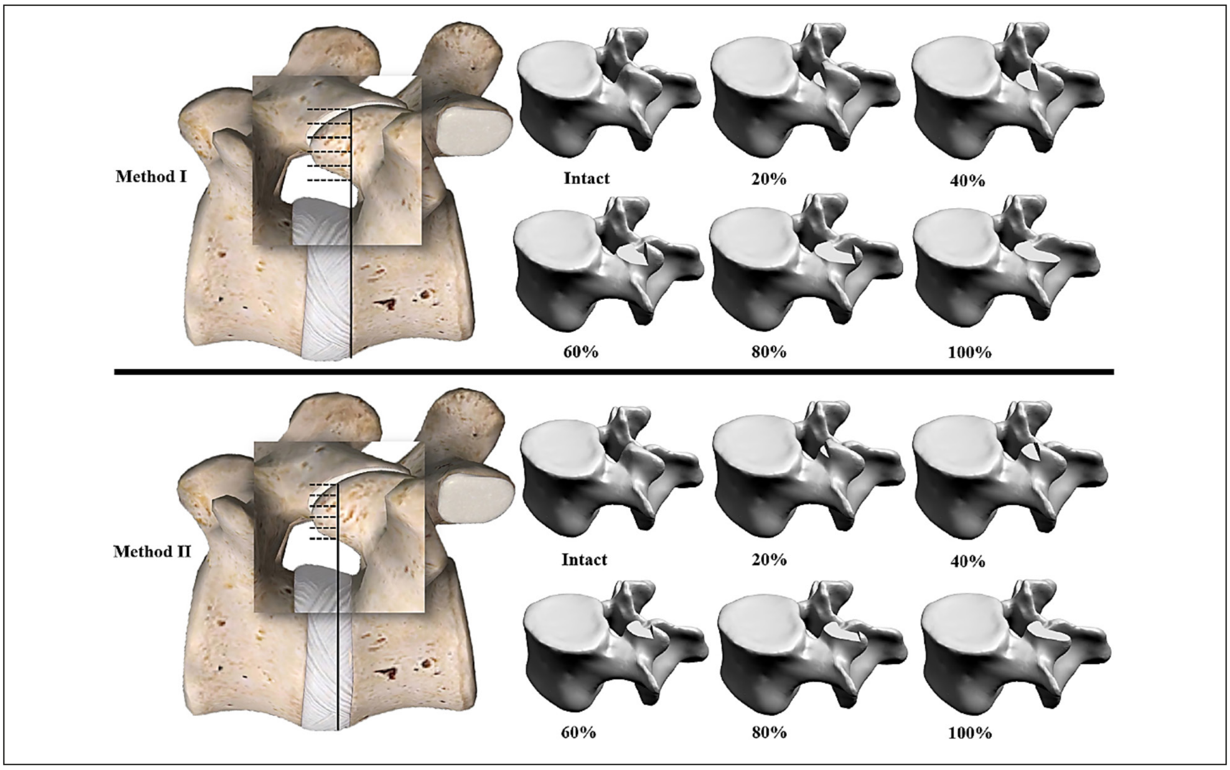

Figure 2. A schematic illustration of graded ventral facetectomy of left superior articular process. Method I, ventral basal part resection of superior articular process. Method II, ventral apical part resection of superior articular process.

Method II (Ventral Apical Part Resection of SAP)

We further subdivided SAP, so that the upper half in the vertical direction of the left SAP above the plane of the superior endplate of the inferior vertebra would be resected into five regions, according to the procedure described in Method I. The amount of bone removed in the FE model corresponded to the removal of 20%, 40%, 60%, 80%, and 100% of the left partial SAP from the ventral to the dorsal side.

Analysis

In each model, the sacrum was fixed in all degrees of freedom, and the loads were applied to the upper surface of the L2 endplate. An axial compressive preload of 400 N was set to simulate the physiological standing load, and a torsional moment of 7.5 N-m was applied to simulate the physiological motions of Flex, Ext, LLB, RLB, LAR, and RAR[8]. ROM was analyzed and compared to the intact model in the respective directions for all cases.

Statistical Analysis

Statistical analyses were performed using SPSS software (ver. 12.0.1; SPSS Inc., Chicago, IL, USA). One-way analysis of variance was used to examine differences in measurements between the sexes. In all analyses, $p < 0.05$ was taken to indicate statistical significance. Each radiological parameter was measured three times by a single observer and the means of the measurements were used for statistical evaluation.

Results

Radiological Measurements

The mean (±SD) values of the segments are summarized in Table II, and differences in the parameters between sexes are shown in Table III.

Distance A is the shortest distance between the horizon line (l_1) of the vertebral posterior margin and the facet surface of the superior

Table II. Segmental variation in radiological measurements (mm±SD).

	L3-L4	L4-L5	L5-S1
Distance A	6.5 ± 1.6	5.0 ± 1.5	4.3 ± 1.7
Distance B	4.7 ± 1.1	3.8 ± 1.4	3.6 ± 1.5
Distance C	17.5 ± 2.3	15.6 ± 2.7	14.0 ± 2.8

Table III. Cox PH regression model estimates for the risk of clinical recurrence.

	L3-L4			L4-L5			L5-S1I		
	Male	Female	p	Male	Female	p	Male	Female	p
Distance AL	6.1 ± 1.5	6.9 ± 1.7	< 0.05	4.6 ± 1.5	5.1 ± 1.7	> 0.05	3.8 ± 1.7	4.2 ± 1.8	> 0.05
Distance AR	6.2 ± 1.5	6.9 ± 1.6	< 0.05	5.0 ± 1.3	5.2 ± 1.6	> 0.05	4.4 ± 1.6	4.7 ± 1.7	> 0.05
Distance BL	4.5 ± 1.1	4.9 ± 1.2	< 0.05	3.7 ± 1.8	3.8 ± 1.2	> 0.05	3.2 ± 1.4	3.6 ± 1.5	< 0.05
Distance BR	4.5 ± 1.0	4.9 ± 1.1	< 0.05	3.6 ± 1.2	3.9 ± 1.2	> 0.05	3.5 ± 1.5	4.1 ± 1.5	< 0.05
Distance CL	17.8 ± 2.1	16.5 ± 2.1	< 0.05	15.9 ± 2.6	14.5 ± 2.8	< 0.05	14.0 ± 2.8	13.3 ± 2.6	> 0.05
Distance CR	18.5 ± 2.1	17.0 ± 2.2	< 0.05	16.9 ± 2.3	15.0 ± 2.6	< 0.05	14.9 ± 2.9	13.7 ± 2.6	< 0.05

Distance A, the shortest distance between the horizon line (l1) of the vertebral posterior margin and facet surface of the superior articular process at the plane of the inferior endplate of the superior vertebra; Distance B, the shortest distance between the horizon line (l2) of the vertebral posterior margin and facet surface of superior articular process at the plane of the superior endplate of the inferior vertebra; Distance C, the projection length of superior articular process on the vertical direction of l2 at the plane of the superior endplate of the inferior vertebra; L, left; R, right.

articular process at the plane of the inferior endplate of the superior vertebra; Distance B is the shortest distance between the horizon line (l_2) of the vertebral posterior margin and the facet surface of superior articular process at the plane of the superior endplate of the inferior vertebra; Distance C is the projection length of superior articular process on the vertical direction of l_2 at the plane of the superior endplate of the inferior vertebra.

Overall, as the spine level decreased, Distances A, B and C also decreased. There were significant differences between the sexes in Distance A and B at L3-L4, as well in Distance B at L5-S1, with shorter distances in males indicating narrower bony intervertebral foramen. The radiological parameters were generally narrower than the diameters of commercially available working cannulas (~7.5 mm in diameter), and therefore foraminoplasty was indispensable for PELD in the lower lumbar region. In addition, males had a significantly longer Distance C (projection length of SAP) compared to females, at all levels except the left length of S1 SAP.

Graded Facetectomy Model Investigation

The ROM in each direction and for each segment in the intact and graded ventral facetectomy models are shown in Figures 3-5. In general, graded facetectomy had a minor effect on flexion and larger effects on lateral bending and axial rotation. The changes in ROM, in each direction and segment, increased with increased extent of resection. In addition, the change in ROM with Method II was much smaller than that with Method I, with the same extent of resection.

At L3-L4, the ROM of 40% facetectomy with Method I increased markedly, by 24% and 28%, in LLB and LAR, respectively, compared to the intact model. However, the ROM increased by only 9% in LLB and 5% in LAR, with 40% facetectomy in Method II. Moreover, a marked increase in ROM was detected with 80% facetectomy in Method II (Figure 3).

At L4-L5, markedly increased ROM with 40% facetectomy in Method I was detected in four directions (LLB, RLB, LAR, RAR), all being larger than 20% of the intact model. In addition, increases of 26%, 33%, and 25% were detected in LLB, RLB, and RAR, respectively, with 60% facetectomy in Method II (Figure 4).

At L5-S1, the general trend of variation in ROM was similar to that at L4-L5, but the increase in ROM with 20% facetectomy in Method I was greater than that at L3-L4 and L4-L5 (Figure 5).

Discussion

With the development of novel instruments and techniques, PELD has been applied to various types of disc herniation, and even to lumbar stenosis[6,8,10]. Foraminoplasty, which requires the use of high-speed endoscopic drills or reamers to undercut the ventral part of the SAP, can provide surgeons with an adequate field of view and operative space to access herniated fragments and simultaneously decompress foraminal and lateral recess stenoses to alleviate radicular pain. Nevertheless, the spinal facet joints play important roles in guiding vertebral motion and resisting compression, shear, rotation, and load bearing. Choi et al[6] suggested that resection should not involve

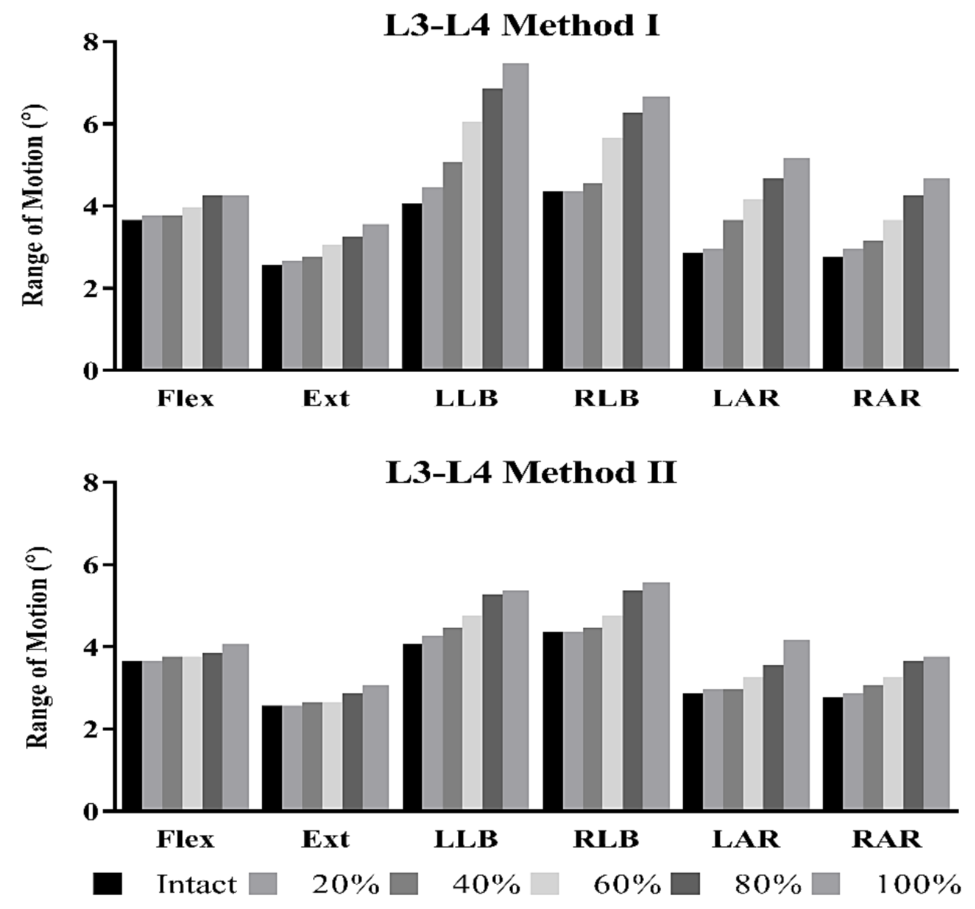

Figure 3. Range of motion after graded ventral facetectomy at the L3-L4. Method I, ventral basal part resection of the superior articular process; Method II, ventral apical part resection of the superior articular process; Flex, flexion; Ext, extension; LLB, left lateral bending; RLB, right lateral bending; LAR, left axial rotation; RAR, right axial rotation.

the articular surface, as preservation of a larger articular surface is important for the maintenance of spinal stability in PELD. However, for a number of reasons, including osteophyte formation, anatomical variation, hypertrophy of the SAP, the long learning curve, and different surgical approaches to PELD, the extent of SAP resection differs among surgeons in actual clinical practice. In addition, there have been no studies regarding foraminoplasty to detect postoperative biomechanical changes in the lumbar region.

First, we performed retrospective measurements on the CT scans of 170 lumbar intervertebral discs to understand the normal working zone of foraminoplasty. Distances A, B and C decreased with decreasing spine level. Distance B, defined as the shortest distance between the posterior lumbar margin and the facet surface of the SAP in the plane of the inferior vertebra superior endplate, had average values of only 4.7, 3.8, and 3.6 mm at L3-L4, L4-L5, and L5-S1, respectively. This base dimension of the foraminoplasty working zone was clinically important and lower than the diameter of around 7.5 mm for commercially available working cannulas. In addition, there were significant sex-related differences in bilateral Distance B at L3-L4 and L5-S1, with smaller dimensions in males indicating a narrower bony intervertebral foramen.

Second, to gain further insight into the biomechanics of lumbar foraminoplasty, we developed and validated an FE model of the L2-sacrum. Then, we designed two methods of graded ventral facetectomy to simulate foraminoplasty. Based on the ROM of the FE model, the results showed that 20% facetectomy in Method I and 60% facetectomy in Method II at L3-L4, 20% facetectomy in Method I and 40% facetectomy in Method II at L4-L5, and 20% facetectomy in Method I and

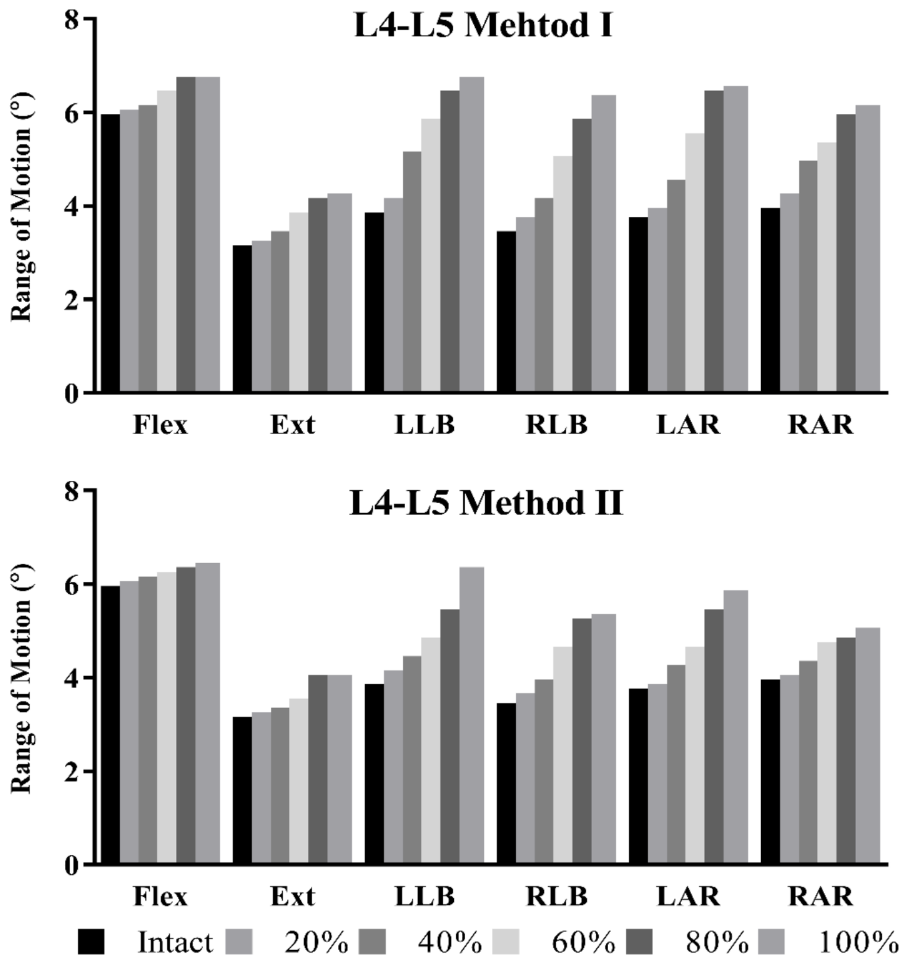

Figure 4. Range of motion after graded ventral facetectomy at the L4-L5. Method I, ventral basal part resection of the superior articular process; Method II, ventral apical part resection of the superior articular process; Flex, flexion; Ext, extension; LLB, left lateral bending; RLB, right lateral bending; LAR, left axial rotation; RAR, right axial rotation.

40% facetectomy in Method II at L5-S1 had minimal influence on the stability of the spine. Due to the extensive resection of facets, the increased ROM may indicate a destabilized motion segment. Moreover, facetectomy in Method I results in a much greater risk of instability compared to the same proportion of facetectomy in Method II. However, to expand the foraminal volume and decompress traversing and exiting nerves as thoroughly as possible, many surgeons attempt to apply Method I for foraminoplasty, even with complete removal of the SAP[8]. This would obviously impact the stability of the lumbar region.

According to Distance C (projection length of the SAP) and the biomechanical results, the appropriate ventral resection extents of the basal part of the SAP (Method I) were rounded up to 4 mm (20%), 3 mm (20%), and 3 mm (20%) on the lateral view at L3-L4, L4-L5, and L5-S1, respectively. The appropriate ventral resection extents of the apical part of the SAP (Method II) were rounded up to 10 mm (60%), 6 mm (40%), and 6 mm (40%) on the lateral view at L3-L4, L4-L5, and L5-S1, respectively. A number of cadaveric and FE studies[17,19,20] of facetectomy-simulated traditional surgery, mainly graded in the direction of the sagittal plane, have been reported. However, graded facetectomy in the ventral direction has not been reported. In 1997, Osman et al[27] examined the lumbar stability of transforaminal decompression in 10 fresh lumbar cadaveric specimens of different segments, and their overall results (ignoring

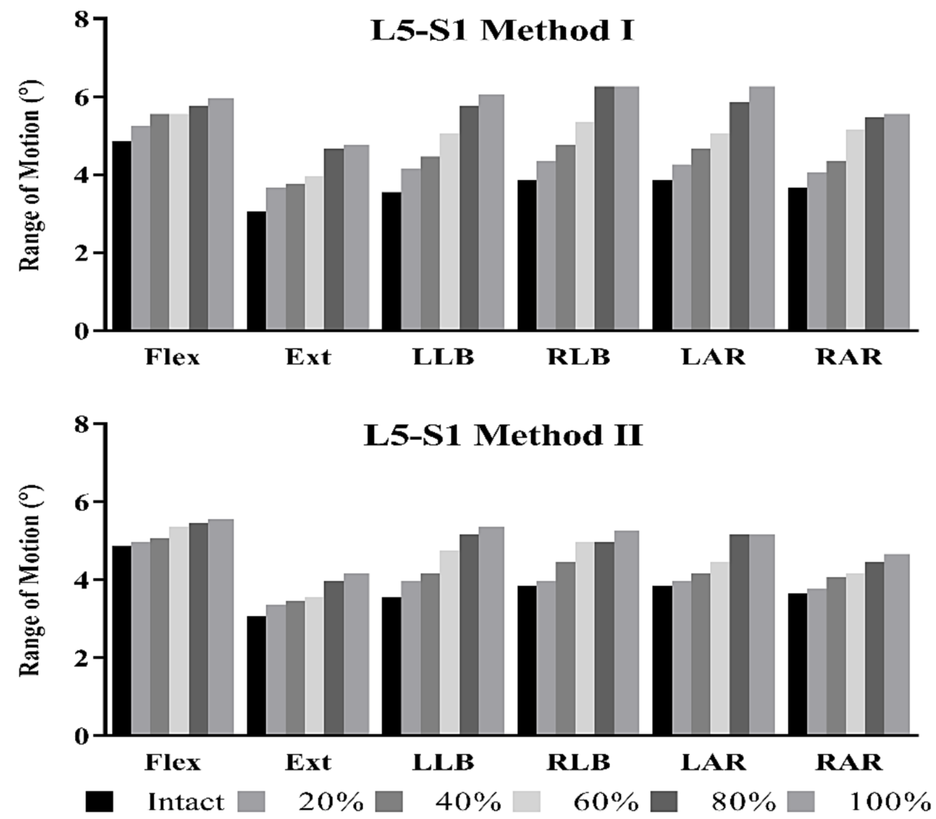

Figure 5. Range of motion after graded ventral facetectomy at the L5-S1. Method I, ventral basal part resection of the superior articular process; Method II, ventral apical part resection of the superior articular process; Flex, flexion; Ext, extension; LLB, left lateral bending; RLB, right lateral bending; LAR, left axial rotation; RAR, right axial rotation.

segmental differences) indicated no differences in multidirectional flexibility in the transforaminal decompression model compared to the intact model. In their study, the anteromedial third of the SAP, and the anterior part of the inferior facet, were removed by transforaminal decompression. However, as their division method proceeded along the curved surface of the SAP, the extent of resection was equivalent to approximately 20% facetectomy in Method I in our study, based on their postoperative CT scans. In addition, the limited number and advanced age of their specimens, along with the lower accuracy of their instruments, may have impacted the eventual outcome.

Limitations

This study had some limitations. As the first study reported biomechanics of foraminoplasty of PELD, the FE model used for simulation was based on a healthy young volunteer to reduce bias from different degeneration models and was simplified by excluding muscle. Pathological models with herniated discs and foraminal stenosis should be used to simulate and investigate the biomechanics of foraminoplasty. The results of the present study should be viewed as a comparative analysis between graded ventral facetectomy models and an intact model. Further cadaveric experiments are required to verify our findings. The effects of partial pediculotomy by PELD, which may further decrease the facet contact area, must be investigated in future studies.

Conclusions

Based on the results of radiological measurements and biomechanical evaluation of lumbar, the appropriate ventral resection extents of the basal part of the SAP (Method I) were 4 mm, 3 mm, and 3 mm on the lateral view at L3-L4, L4-L5, and L5-S1, respectively. The appropriate ventral resection extents of the apical part of the SAP (Method II) were 10 mm, 6 mm, and 6 mm on the lateral view at L3-L4, L4-L5, and L5-S1, respectively. It is necessary to measure Distances B and C on preoperative CT scans to determine the extent of intraoperative resection and ensure sufficient stability of the spine.

Conflict of Interest
The Authors declare that they have no conflict of interests.

Ethics Approval
The study was approved by the Institutional Review Board of the Tongji Hospital, Tongji Medical College (ethical code Number: 81571816). All procedures were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

Informed Consent
All patients signed a written informed consent.

Data Availability
The data that support the findings of this study are available on request from the corresponding author.

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No funding was received for this study.

Authors' Contribution
JSD, MG, XLD, GYW, and WX designing and conducting experiments, collection of results, drawing the diagram, statistical analyses, funding acquisition, conceptualization of the idea, and writing and revising the manuscript. All authors read and approved the final manuscript.

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