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The segment-dependent changes in lumbar intervertebral space height during flexion-extension motion

M. Fu,
Q. Ye,
C. Jiang,
L. Qian,
D. Xu,
Y. Wang,
P. Sun,
J. Ouyang

Southern Medical University, Baiyun District, Guangzhou, China

Objectives

Many studies have investigated the kinematics of the lumbar spine and the morphological features of the lumbar discs. However, the segment-dependent immediate changes of the lumbar intervertebral space height during flexion-extension motion are still unclear. This study examined the changes of intervertebral space height during flexion-extension motion of lumbar specimens.

Methods

First, we validated the accuracy and repeatability of a custom-made mechanical loading equipment set-up. Eight lumbar specimens underwent CT scanning in flexion, neural, and extension positions by using the equipment set-up. The changes in the disc height and distance between adjacent two pedicle screw entry points (DASEP) of the posterior approach at different lumbar levels (L3/4, L4/5 and L5/S1) were examined on three-dimensional lumbar models, which were reconstructed from the CT images.

Results

All the vertebral motion segments (L3/4, L4/5 and L5/S1) had greater changes in disc height and DASEP from neutral to flexion than from neutral to extension. The change in anterior disc height gradually increased from upper to lower levels, from neutral to flexion. The changes in anterior and posterior disc heights were similar at the L4/5 level from neutral to extension, but the changes in anterior disc height were significantly greater than those in posterior disc height at the L3/4 and L5/S1 levels, from neutral to extension.

Conclusions

The lumbar motion segment showed level-specific changes in disc height and DASEP. The data may be helpful in understanding the physiologic dynamic characteristics of the lumbar spine and in optimising the parameters of lumbar surgical instruments.

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- M. Fu, MD, PhD, Dr.,
- C. Jiang, MS, Masters student,
- L. Qian, MD, PhD, Dr,
- D. Xu, MD, PhD, Dr.,
- Y. Wang, MD, PhD, Dr.,
- P. Sun, MD, PhD, Lecturer,
- J. Ouyang, MD, PhD, Professor, Director of Department of Anatomy, Department of Anatomy, Guangdong Provincial Key Laboratory of Medical Biomechanics, Southern Medical University, Baiyun District, Guangzhou, Guangdong, China.
- Q. Ye, MS, Attending Doctor, Department of Radiology, The Third Affiliated Hospital of Southern Medical University, Tianhe District, Guangzhou, Guangdong, China.

Correspondence should be sent to J. Ouyang; email: jouyang@126.com

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Article focus

- To examine the changes of the intervertebral space height during flexion-extension motion of the lumbar spine.

Key messages

- The lumbar motion segment showed level-specific changes of lumbar intervertebral space distance during flexion-extension motion.
- The changes in disc height and DASEP (distance between the adjacent two pedicle screw entry points) from neutral to flexion were greater than from neutral to extension; the changes in disc height at L4/5 were different to those at the other two levels (L3/4, L5/S1) during flexion-extension motion.
- The data may be used in understanding the physiologic dynamic characteristics of the lumbar spine and in optimising the parameters of lumbar surgical instruments for basic research.

Strengths and limitations

- The study was performed *in vitro* and the sample size was limited.

Introduction

With the emergence of degenerative lumbar diseases, an increasing number of research studies have focused on the biomechanical properties of the lumbar spine. Recent studies have suggested that there is a segment-dependent difference in the structure of lumbar discs and kinematics of the lumbar spine.[1-3] These characteristics may be a reason for the difference in clinical pathological appearance between different lumbar motion segments. For example, reports showed that lumbar degenerative spondylolisthesis and lumbar herniation are often found at the L4/5 and L5/S1 levels, respectively.[4,5] However, the relationship between the segment-specific difference and the clinical events is unclear. Accurate understanding of the spinal structural functions is important to explain the biomechanical factors of spinal pathologies. Therefore, many biomechanics studies have aimed to examine the lumbar complex structures and motion patterns of the lumbar spine.

Studies investigated the geometric characteristics of different segmental human lumbar intervertebral discs by using MRI *in vivo* or *in vitro*.[1,2,6-9] Meanwhile, some authors assessed the kinematics of the lumbar spine. Cadaveric studies measured lumbar segment kinematics by applying six degrees of freedom (6DOF) or flexion-extension motion, with or without a compressive load.[10,11] *In vivo* motion of the lumbar spine has often been evaluated by using three-dimensional (3D) fluoroscopic imaging and CT or MRI.[12-16] However, these only focused on the static anatomical characteristics or pure range of motion of the lumbar spine. Few studies have reported the segment-dependent changes in the lumbar intervertebral space height during the dynamic motion of the lumbar spine.

We aimed to measure the immediate changes in lumbar intervertebral space height at different levels during flexion-extension motion *in vitro* study. This would aid in a better understanding the motion patterns and biomechanical mechanisms of the lumbar spine. We used a new validated method to obtain kinematic CT images of normal specimens of the human lumbar spine from L3 to S1. We then reconstructed the lumbar spine models three-dimensionally, and measured the related parameters on the 3D models. We hypothesised that the changes in the intervertebral space height at different levels and positions have different characteristics.

Materials and Methods

Specimens. Eight fresh-frozen human cadaveric lumbar spine specimens (L3 to S1, mean age 51.5 SD 10.2 years) were investigated in this study. None of the lumbar specimens had previous spinal surgery. We also excluded the specimens with bridging osteophytes, obvious osteoporosis and other severe lumbar degenerative diseases as determined by CT images read by a senior radiologist (Q.Y). Before testing, the lumbar specimens were thawed for 12 hours at room temperature (approximately 25°C). The paravertebral muscles were carefully resected, leaving the discs, ligaments, facet joints and posterior elements intact. During testing, the lumbar specimen was wrapped with saline-soaked towels.

Instruments. Custom-made experimental equipment was used (Fig. 1). The frame was constructed with one piece of hard wood (750 × 200 × 50 mm^3) and 12 steel rods (diameter 10 mm). Each of the load bearing beam was installed with two pulleys. The junctions of the frame were rigidly welded together, but the pulleys could slide on the beam freely. Meanwhile, a specimen-fixed disk, with a constant arm of 0.1 m pure moment arm, was used. The pure moment could be loaded by hanging a corresponding weight.

Procedures. Each specimen was prepared by anchoring the L3 and S1 vertebrae in cups by using polymethyl methacrylate, and pins with the L4/5 disc space orientated horizontally. Four aluminium balls (diameter 2 mm) were carefully inserted in the vertebral bone, from the L3 to S1 vertebrae, respectively, as markers. Two of the markers were located at the lumbar vertebral body, and the other two were located at the vertebral laminae. The caudal end of the specimen was then firmly mounted in the custom-made experimental frame so that the lumbar levels (L3/4, L4/5 and L5/S1) could move freely. The entire apparatus with the lumbar specimen was placed on the CT bed (Toshiba, Aquilion, Japan); in-plane pixel size, 0.26 mm and slice thickness, 1 mm. A 6 Nm pure moment was applied on the lumbar spine to create a flexion-extension motion, with no preload applied. Three pre-conditioning cycles were applied to the specimen before being scanned. The CT scanner would then capture the lumbar specimen at the neutral, flexion and extension positions (Fig. 1). The experimental frame was immobile against the CT bed for the duration of the CT scanning. The data, which were saved in a Digital Imaging and Communications in Medicine (DICOM) format from the CT images, were imported into Mimics 15.0 (Materialise NV, Leuven, Belgium), a 3D reconstruction software. The 3D models of the lumbar vertebrae and aluminium balls were then created.

Repeatability and accuracy analyses. To validate the repeatability and accuracy of the method, we needed to calculate the range of motion of the lumbar spine during flexion-extension motion, which was based on the motion of the aluminium balls (Fig. 2). First, the 3D models of the marker balls, located at L3/4 of flexion and neutral lumbar models, were imported into Geomagic Studio 2013 software (Geomagic, Inc., Morrisville, North Carolina) in Stereolithography (STL)format. The marked points were achieved by fitting the centre of balls using a "feature-creating" function. The co-ordinate data of all the points were registered. The flexion range of motion

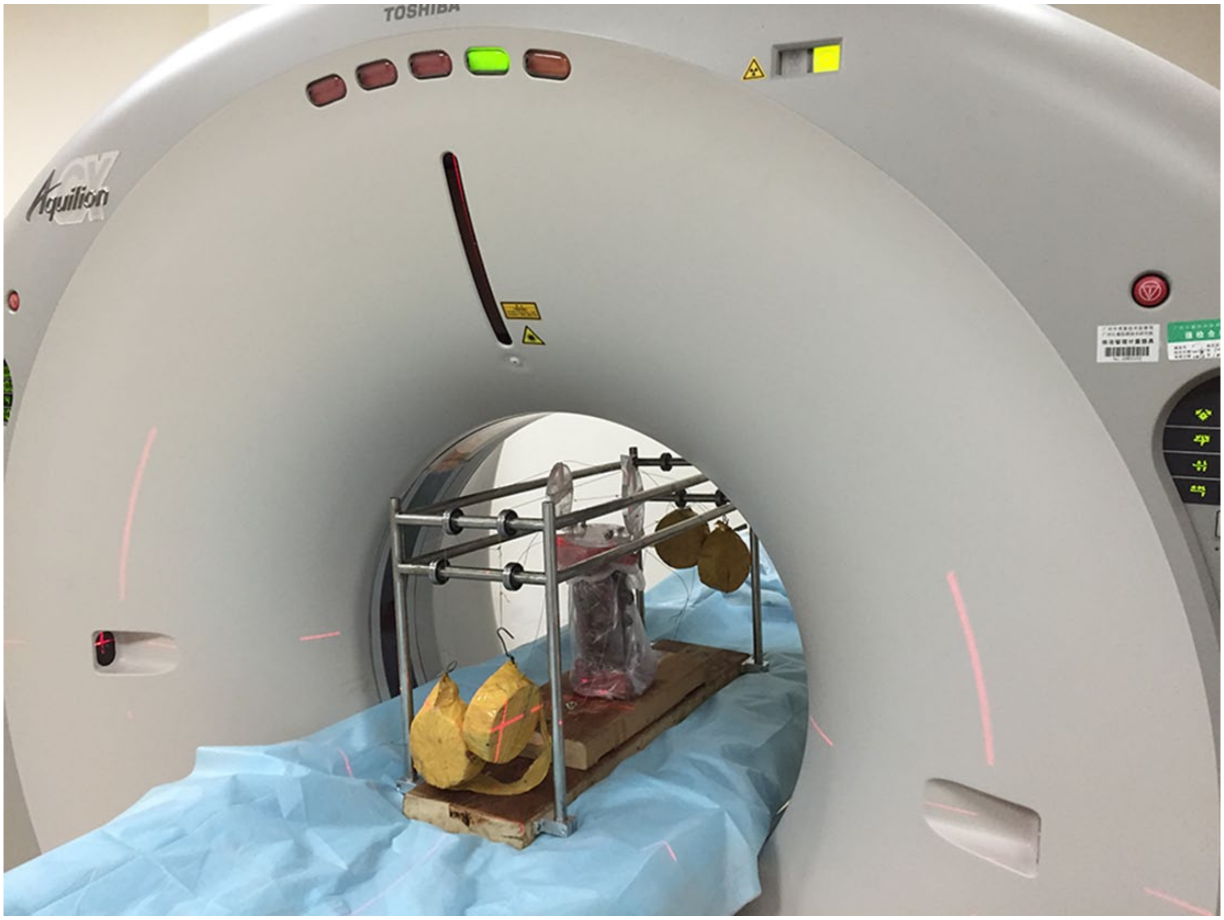

Fig. 1

An experimental set-up of CT scanning of the lumbar specimen by using the equipment with a 6 Nm pure moment.

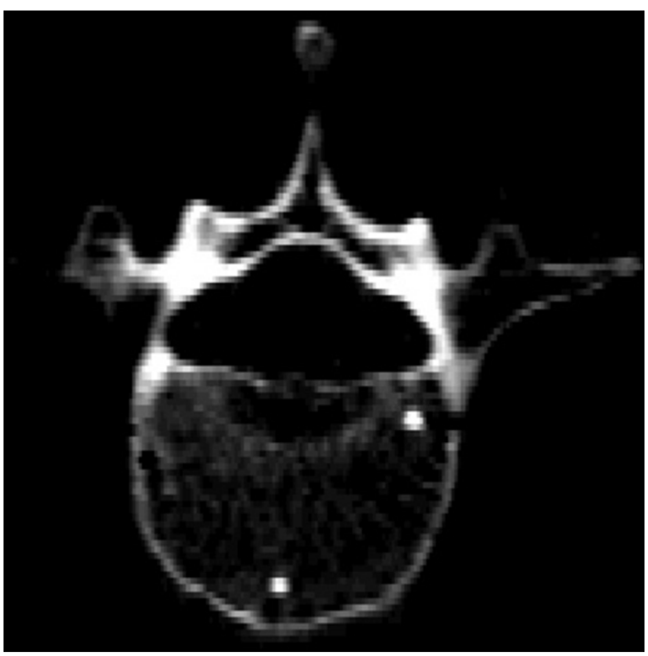

Fig. 2

CT image of the spine segment. The white dots are two of the aluminum ball markers.

could be measured with the "N-Point Alignment" function of the software at the L3/4 level. In this way, the ranges of motion of flexion and extension were achieved at L3/4, L4/5 and L5/S1 level, respectively.

To evaluate the repeatability of the custom-made experimental apparatus in simulating dynamic spine motion, one lumbar spine applying 6 Nm pure moment for flexion-extension motion was reproduced four times. Meanwhile, CT was used to scan the lumbar spine specimens at neutral, flexion, and extension positions. The ranges of motion of each lumbar unit (L3/4, L4/5 and L5/S1) were calculated by using the motion of aluminium markers in the Geomagic Studio software. Data were expressed as mean and standard deviation (SD). The SD could be used to examine the repeatability of the custom-made experimental apparatus in reproducing the lumbar spine motion.

To validate the accuracy of using the method in simulating the dynamic motion of the lumbar spine, the CT data at the neutral, flexion, and extension positions were obtained. The range of motion of each lumbar unit (L3/4, L4/5 and L5/S1) was calculated by using the aluminium markers in Geomagic Studio software. Meanwhile, a common 3D motion-analysis system[17,18] was used to

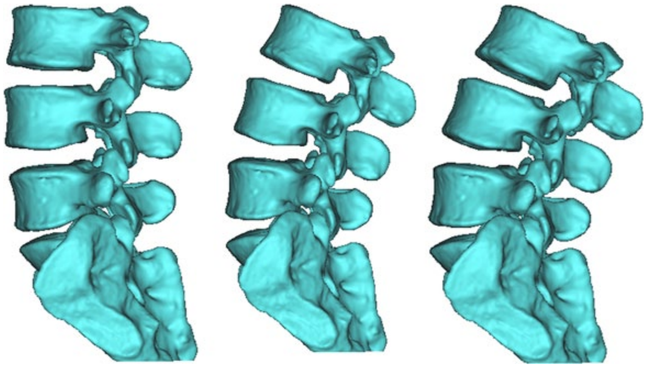

Fig. 3a Fig. 3b Fig. 3c

Three-dimensional models of the lumbar spine from the CT data from the different positions (a: Flexion, b: Neutral, c: Extension).

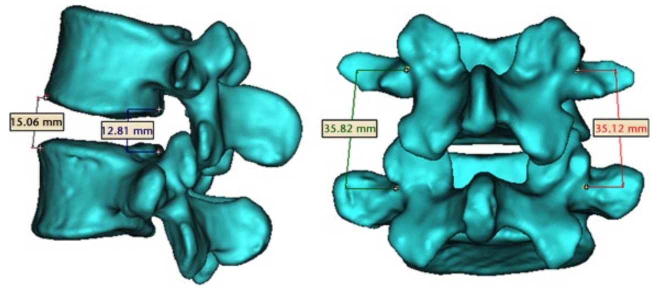

Fig. 4a Fig. 4b

The method of measuring the disc height and DASEP. a) Measurement of the anterior posterior disc heights. b) Measurement of the DASEP.

Table I. Validation of the repeatability of the method in reproducing the vertebral positions by using the results of 4 repeats of one specimen

	L3/4	L4/5	L5/S1
Flexion (°)	5.53 (SD 0.50)	8.45 (SD 0.35)	9.50 (SD 0.62)
Extension (°)	2.16 (SD 0.31)	3.02 (SD 0.36)	4.50 (SD 0.35)

The data were mean standard deviation (SD) of the range of motion in the different levels

evaluate the range of motion of each lumbar unit with the same moment. All the data were expressed as mean ± standard deviation (SD). The two groups of data were compared with each other to examine the accuracy of the current method.

Measurements and statistical analysis. All the measurements were based on the 3D lumbar models (Fig. 3) which were created from the CT images of the lumbar spine at different positions by using the Mimics software. The data included the anterior disc height, posterior disc height (Fig. 4a), and the distance between the adjacent two screw entry points, which were widely used in clinical practice (Fig. 4b). The anterior disc height was defined as the distance between the two most anterior points of the adjacent endplates. The posterior disc height was defined as the distance between the two most posterior points of the adjacent endpoints in the mid-sagittal plane. The DASEP was defined as the distance between the adjacent two pedicle screw entry points of the posterior approach. The screw entry points were defined as the junction of the pars interarticularis with the transverse process and the mamillary process/superior articular process of the segment of interest.[19,20] The neutral-flexion changes in anterior disc height were calculated by subtracting the distance in the neutral position from the distance in the flexion position. In the same way, we can determine the changes in disc height and DASEP in other conditions.

The paired sample *t*-test was used to compare the accuracy of the custom-made experimental apparatus in reproducing the dynamic spine motion. One-way analysis of variance was used to compare the differences in disc height and DASEP, and the changes in the distance during flexion-extension motion of the different vertebral levels. Statistical significance was set at $p < 0.05$. Statistical analysis was performed with the SPSS 20.0 software (IBM Corp., Armonk, New York).

Results

Repeatability and accuracy test. To evaluate the repeatability, one specimen successfully reproduced flexion-extension motion four times with a 6 Nm pure moment by using the experimental apparatus. The ranges of motion in the different lumbar segments are listed in Table I. The SD of the range of motion was determined to be 0.31° to 0.62° in different lumbar segments. To validate the accuracy of the method, we compared the range of motion that was calculated with the current method, with the data from the 3D motion analysis system. The result showed no significant differences ($p > 0.05$) between the two methods (Fig. 5).

Lumbar disc space height and the DASEP. In the neutral position, anterior disc height (L3/4: 13.46 SD 2.38 mm, L4/5: 15.18 SD 2.09 mm, L5/S1: 15.93 SD 3.12 mm) was similar in the different lumbar segments, as was the posterior disc height (L3/4: 8.01 SD 1.33 mm, L4/5: 9.15 SD 1.93 mm, L5/S1: 7.50 SD 1.19 mm). The DASEP was significantly longer at L3/4 than at L5/S1 ($p < 0.05$). In the flexion position, the posterior height was less at L3/4 than at L4/5 ($p < 0.05$). In the extension position, the anterior disc height, posterior disc height and the two sides of the DASEP had no significant differences at L3/4, L4/5 and L5/S1, respectively. All the data are listed in Table II.

Change in lumbar disc space height and the DASEP during flexion-extension. The change in anterior disc height gradually increased from the upper to the lower levels (L3/4: 1.56 ± 0.30 mm, L4/5: 2.06 ± 0.62 mm, L5/S1: 2.50 ± 0.93 mm), from neutral to flexion (Fig. 6). A significant difference was observed between the L3/4 and L5/S1 levels ($p < 0.05$). The change in the posterior disc height (L3/4: 1.38 ± 0.29 mm, L4/5:1.83 ± 0.28 mm, and L5/S1: 2.14 ± 0.62 mm) also had an increasing trend. In particular, the change in posterior disc height was significantly less at L3/4 than those at L5/S1. However, from neutral to extension, the change in disc height and the

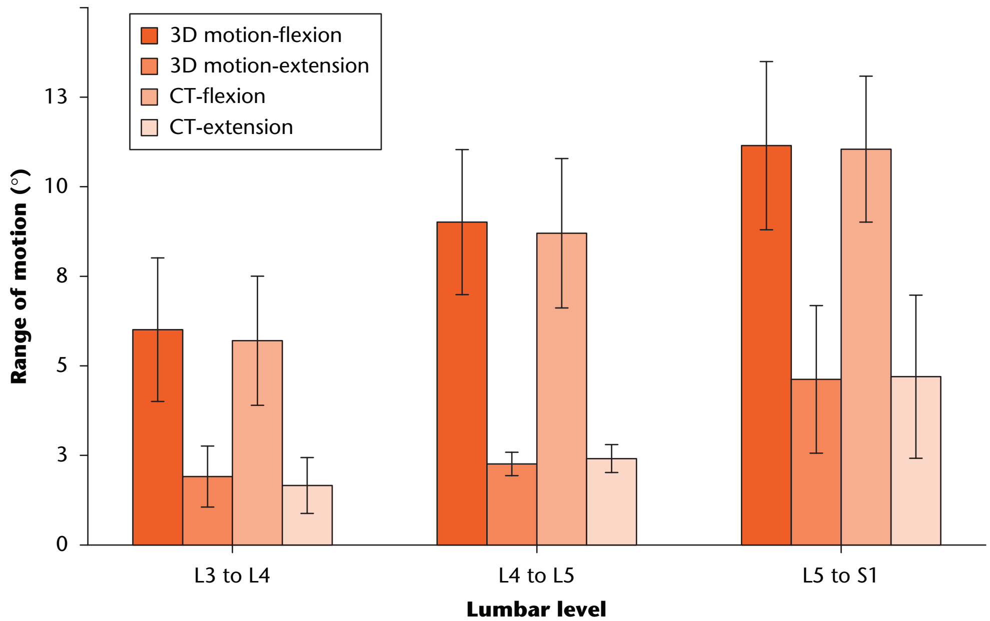

Fig. 5

Comparison of the range of motion of the two different methods. The three-dimensional (3D)-flexion/extension is the measurement of the range of flexion/extension in the 3D motion analysis system method. CT flexion/extension is the measurement of the range of flexion/extension by using the current method in the study.

Table II. The disc height and distance between the adjacent two pedicle screw entry points (DASEP) at different levels

		Anterior disc height (mm)	Posterior disc height (mm)	Left DASEP (mm)	Right DASEP (mm)
	Neutral	13.46 (SD 2.38)	8.01 (SD 1.33)	32.50 (SD 4.40)	32.85 (SD 3.80)
L3/4	Flexion	12.10 (SD 2.59)	9.19 (SD 1.72)	35.15 (SD 3.88)	35.51 (SD 3.14)
	Extension	14.92 (SD 2.49)	7.45 (SD 1.40)	30.74 (SD 4.69)	31.09 (SD 4.18)
	Neutral	15.18 (SD 2.09)	9.15 (SD 1.93)	29.79 (SD 3.64)	29.56 (SD 3.28)
L4/5	Flexion	12.98 (SD 2.27)	10.99 (SD 1.69)	33.75 (SD 3.13)	33.19 (SD 2.84)
	Extension	16.05 (SD 2.01)	8.47 (SD 1.96)	28.36 (SD 4.00)	28.11 (SD 3.54)
	Neutral	15.93 (SD 3.12)	7.50 (SD 1.19)	27.87 (SD 3.94)	28.02 (SD 3.83)
L5/S1	Flexion	13.44 (SD 2.65)	9.54 (SD 1.11)	31.94 (SD 4.01)	32.02 (SD 3.95)
	Extension	17.02 (SD 3.22)	7.00 (SD 1.06)	26.20 (SD 3.44)	26.29 (SD 3.06)

Values are presented as mean ± SD
DASEP, distance between adjacent screw entry points (DASEP)

DASEP showed no statistical differences between any two motion segments (Fig. 7).

No statistically significant difference was found between the changes in anterior and posterior disc heights at the same level from neutral to flexion (Fig. 6). However, the change in anterior disc height was significantly greater than the change in posterior disc height at L3/4 and L5/S1 from neutral to extension (Fig. 7).

Discussion

This study investigated the dynamic changes in lumbar intervertebral space height during flexion-extension motion in an *in vitro* experimental setup. We first validated the repeatability and accuracy of the method for reproducing the motion of the lumbar spine with a 6 Nm pure moment. The data showed that this method had high accuracy and repeatability in determining the vertebral segment position of the lumbar spine. A similar method has been used by other studies and examined for its usability.[17,21,22] We simply validated the accuracy and repeatability of the new experimental equipment.

Quantitative knowledge of lumbar vertebral kinematics is critical to understanding spinal pathologies and in optimising spinal instruments. We focused on the changes in lumbar intervertebral space height during flexion-extension motion. Anterior disc height increased from L3/4 to L5/S1 in all positions, although not statistically significantly in this study. Posterior disc height at L4/5 was greater than at the other two segments in all positions. We first measured the changes in lumbar disc space height and the DASEP during flexion-extension. The changes in the DASEP were similar between the two sides, and the changes in the posterior disc height were greater at the lower levels (L4/5, L5/S1) than at the upper

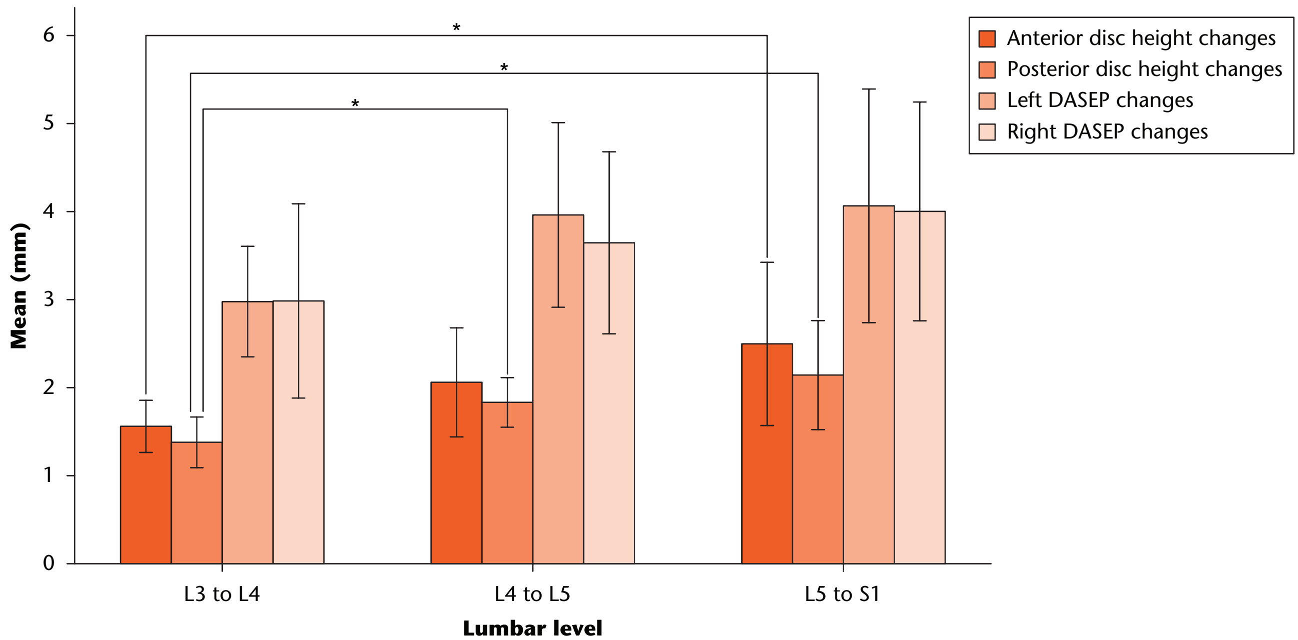

Fig. 6

The changes in disc height and distance between the adjacent two pedicle screw entry points (DASEP) of the lumbar spine from neutral to flexion. *indicates significant difference. One-way analysis of variance test. Values of $p < 0.05$ were deemed significant.

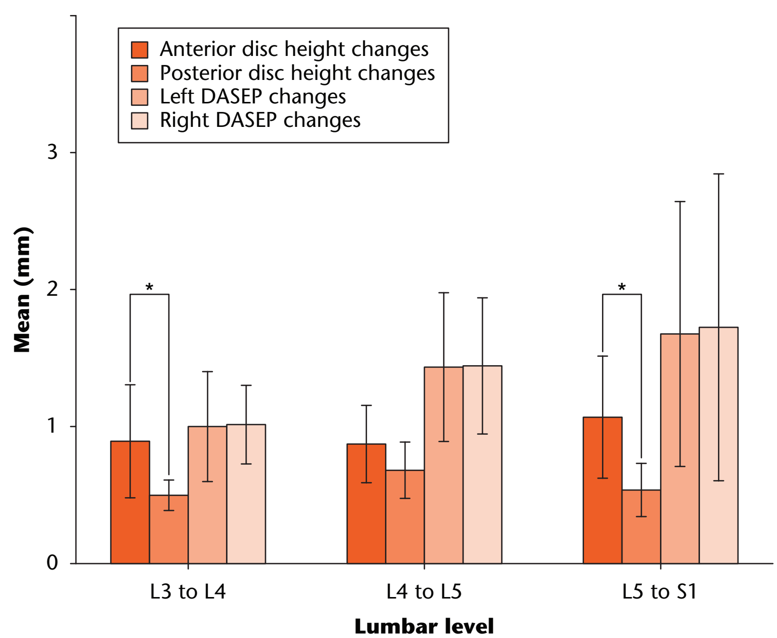

Fig. 7

The changes in disc height and distance between the adjacent two pedicle screw entry points (DASEP) of the lumbar spine from neutral to extension. .*indicates significant difference. One-way analysis of variance test. Values of $p < 0.05$ were deemed significant.

level (L3/4) from neutral to flexion. In general, the changes in the lumbar intervertebral space height (anterior disc height, posterior disc height, left DASEP and right DASEP) were greater in neutral-flexion motion than in neutral-extension motion.

Many studies have investigated the biomechanics of the lumbar spine, including those that described the morphological features of human lumbar discs and examined the range of motion or biomechanical responses of the lumbar spine to external loads. Recently, Zhong et al[1] measured the *in vivo* morphology of lumbar intervertebral discs and found that the anterior annulus fibrosus was longer than the posterior annulus fibrosus at all lumbar segments except at L5/S1, where both were similar in length. Edmondston et al[8] evaluated the influence of sagittal plane position on lumbar intervertebral disc height and nucleus displacement as seen on MRI in a small asymptomatic population. They found a significant increase in measured anterior disc height of 1.1 mm and anterior displacement of the nucleus of 6.7%. Furthermore, kinematic studies of the lumbar segment revealed segmental specificity as well. Yamamoto et al[23] performed a flexion-extension test by loading a pure moment of 10 Nm on cadaveric lumbar specimens and measured a higher range of motion at lower levels (L4/5, L5/S1) than at higher levels. Wu et al[13] investigated *in vivo* motion of the lumbar spine during a weight-lifting activity. Their data showed that the lower lumbar motion segments L4/5 and L5/S1 had larger anterior-posterior and proximal-distal translations, than the upper lumbar segments. However, few studies have reported dynamic changes in lumbar intervertebral space height during flexion-extension and there is little data elucidating the potential relationship between the change in disc height and the biomechanics of the lumbar spine.

In our study, the anterior disc height gradually increased from L3/4 to L5/S1 in all the lumbar positions (neutral, flexion and extension). However, the posterior disc height was greater at L4/5 than at the other two levels in all positions, but without statistically significant differences. The DASEP gradually decreased from L3/4 to L5/S1 and they also had no significant differences between the different levels. These data may help in understanding the distinct kinematic features of the lumbar spine, and can serve as a guide in optimising the parameters of lumbar instruments such as artificial lumbar discs, artificial lumbar facet joints, and lumbar fusion cages.[24-27] The changes in disc height were greatest at L5/S1 from neutral to flexion, but the differences were not significant between the levels from neutral to extension. This may be related to the range of motion of the lumbar spine and the material properties of the annulus fibrosus.[1,28,29] In addition, we found that the changes in anterior and posterior disc heights were similar at L4/5 from neutral to extension, but the changes in anterior disc height were significantly greater than those in posterior disc height at L3/4 and L5/S1 from neutral to extension.

The present study has several limitations. First, it was performed *in vitro*. Although the data are useful for understanding the kinematics of lumbar spine and in performing the relative laboratory experiments, they may be different from those obtained in *in vivo* testing. Our future work will take into consideration both healthy subjects and a symptomatic population with intervertebral disc degeneration, and we will perform *in vivo* testing. Also, the sample size was limited. Although we revealed the difference in the changes in disc height and DASEP at different levels during the flexion-extension process, we could not analyse the effects of age and gender on vertebral kinematics. Hence, we only measured the lumbar spine data from L3 to S1. Future work should overcome these limitations. Finally, we only detected changes in disc height and DASEP in flexion-extension rather than measured in 6DOF spine kinematics, which would provide a better understanding of the kinematics of the lumbar spine. Despite these limitations, this study systematically examined the changes in disc height and DASEP in the flexion-extension motion.

In conclusion, this study investigated human lumbar intervertebral space height and changes in height in flexion-extension motion. Overall, the changes in disc height and DASEP were greater from neutral to flexion than from neutral to extension. Specifically, the changes in disc height at L4/5 significantly differed from those at the other two levels. The changes in anterior and posterior disc heights were similar at L4/5, whether from neutral to flexion or from neutral to extension. The data may give us a better understanding of the physiological characteristics of lumbar motion and potential biomechanical mechanisms of lumbar disease development. These data may be used in optimising the parameters of artificial lumbar instruments in clinical practice and basic research, and in developing segment-specific surgical treatments for restoring native spine function.

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Author Contributions

- M. Fu: Study concepts, Study design, Literature design, Experimental studies, Data analysis, Manuscript preparation.
- Q. Ye: Experimental studies, Study design.
- C. Jiang: Experimental studies.
- L. Qian: Data analysis.
- D. Xu: Study design.
- Y. Wang: Experimental studies.
- P. Sun: Study concepts, Study design.
- J. Ouyang: Guarantor of integrity of entire study.

ICMJE COI Statement

- None declared.