Segmental Coupling Effects during Correction of Three-Dimensional Lumbar Deformity Using Lateral Lumbar Interbody Fusion

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Introduction

Degenerative lumbar scoliosis (DLS) is one of the most difficult clinical conditions to understand in the lumbar spinal disorders because its pathology and mechanism have not been fully elucidated. Deformity in DLS is primarily based on wedge disc deformity in a coronal plane; however, it has been considered to accompany axial rotation. Coexistence of the wedge and axial rotational deformity has been reported as one of the relevant factors of progression of the spinal deformity.[1] Currently, the various corrective instrumentation procedures have been performed even for highly degenerative scoliosis. However, indication and clinical results of corrective surgery for such three-dimensional (3D) deformity have been controversial.[2]

Although importance of axial rotational deformity in DLS has been recognized, limited information on the segmental axial rotational angles in the DLS patients is available in the literature. The axial rotational deformity has been typically determined by means of evaluating positions of pedicles projected on plain radiograms.[3] Because of 3D nature of the spinal deformity in DLS, it is difficult to accurately measure rotational angles about three anatomical axes using two-dimensional (2D) image data.

In recent years, lateral lumbar interbody fusion (LLIF) has been applied for restoration of the disc height, correction of deformity and stabilization for DLS and its usefulness has been reported.[4-6] The LLIF procedure is a minimally invasive procedure in preserving anterior and posterior longitudinal ligaments intact. In the LLIF procedure, restoration of disc height causes tensioning of the anterior and posterior longitudinal ligaments, which is called “ligamentotaxis” and has been considered to provide posterior neural decompression, correction of spinal alignment and stabilization of the motion segment. Although some studies have addressed disc height restoration and deformity correction by LLIF, correlation between the disc height and the amount of deformity correction has not been analyzed in a quantitative manner. [4, 5]

The aim of the present study is two-fold; first, to quantitate segmental rotational deformities in 3D and to clarify correlations between the rotational angles about three anatomical axes in patients with lumbar degenerative disease, and second, to evaluate the effect of LLIF procedure on correction of 3D deformity using patient-specific 3D-CT models.

Material and Methods

Subject Selection

The study group included 28 subjects with lumbar degenerative disease (14 subjects with L3/4 and 14 with L4/5 affected), including spondylosis, degenerative scoliosis, and degenerative spondylolisthesis, in whom LLIF was performed to relieve the neuropathy (e.g., pain, gait disturbance) and low back pain at our institution from June 2014 to July 2016 (Table 1). Patients with correction surgery for adult spinal deformity with low back pain only were excluded. LLIF was performed to achieve correction and nerve decompression. After undergoing LLIF using eXtreme lumbar interbody fusion (XLIF) cage (XLIF®; NuVasive Inc., California, USA) in the lateral position, the posterior side was stabilized with in situ percutaneous pedicle screws (PPS) in the prone position. PPS insertion was performed without any accompanying corrective procedure (e.g., posterior osteotomy, compression, distraction manipulation). This study was approved by the hospital's ethics committee.

Imaging Studies

Each subject underwent CT imaging (CT machine: SOMATOM Definition AS+®; SIEMENS Healthineers Inc., JAPAN, tube voltage: 120 kV, tube current: approximately 120 mAs, field of view: approximately 250 × 180 mm, image matrix: 512 × 512, slice increment: 5 mm, slice thickness: 5 mm) in a supine position preoperatively and three months after surgery. 3D vertebral models of the lumbar spine were created using 3D reconstruction software (Mimics®;

Materialise Inc., Leuven, Belgium). In the postoperative 3D vertebral models, pedicle screws and intervertebral cages were excluded from the models.

3D Alignment Analyses

Posterior wall models were created from the vertebral models for 3D alignment analyses. Eigenvectors of each posterior wall were calculated to determine 3D orientation of the posterior wall. A Cartesian (X-Y-Z) local coordinate system was set on each posterior wall in which an origin was set on a centroid of the posterior wall and orientation was determined by the eigenvectors. The X, Y and Z axes corresponded to mediolateral, posteroanterior and craniocaudal axes, respectively. The coronal (XZ) plane, sagittal (YZ) plane, and transverse (XY) plane were defined from these X-Y-Z axes. The rotations of the superior vertebral body relative to the inferior vertebral body in the adjacent two vertebral bodies were expressed using Eulerian angles in a transverse plane-sagittal plane-coronal plane (Z-X-Y) sequence. The wedge angle, lordosis angle and axial rotation angle were defined by the Eulerian angles in the coronal plane, sagittal plane and axial plane, respectively. A positive value of the lordosis angle was defined as lordosis and the negative value as kyphosis (Figure 1A, 1B).

Disc height measurement

Three-dimensional disc height distribution was measured by the least distances between each point of the lower bony endplate of the superior vertebral body and the superior bony endplate of the inferior vertebral body and the mean value of the least distances was determined as the disc height (Figure 1C).[7]

Spinopelvic parameter measurement

The Cobb angle was measured on a standing anteroposterior radiographic image. Lumbar lordosis (LL), thoracic kyphosis (TK), sagittal vertical axis (SVA), sacral slope (SS), pelvic tilt (PT), and pelvic incidence (PI) were measured on standing lateral radiographic images.

Statistical Analyses

The rotational angles, disc heights, and spinopelvic parameters measured preoperatively and postoperatively were compared by paired *t*-tests. Correction rates of these values due to surgery were calculated by |preoperative value - postoperative value|/preoperative value. For the correlation between the two groups, Pearson's correlation coefficient and a *t*-test were used. Statistical significance was defined as $P < 0.05$. The results were shown as mean ± standard deviation (SD).

Results

Correlations between the rotational angles (before LLIF)

A strong positive correlation was found between the wedge angle and the axial rotation angle ($r = 0.718$, $P < 0.001$) in the patients with lumbar degenerative disease preoperatively (Figure 2).

Effect of LLIF procedure on correction of 3D segmental deformities

The wedge angle decreased after surgery ($P < 0.001$) from the preoperative value of 8.4° ± 5.4° (range: 0.8° - 25.6°) to the postoperative value of 3.8° ± 3.1° (range: 0° - 9.7°) by a correction rate of 55% (-4.6° ± 3.5°). The lordosis angle increased after surgery ($P < 0.01$) from the preoperative value of 5.7° ± 5.3° (range: -7.3° to 17.5°) to the postoperative value of 7.8° ± 5.2° (range: -1.1° to 17.2°) by a correction rate of 37% (+2.1° ± 4.0°). The axial rotation angle decreased after surgery ($P < 0.001$) from the preoperative value of 5.9°±4.2° (range: 0.7° - 21.1°) to the postoperative value of 3.8°±3.4° (range: 0.1° - 13.7°) by a correction rate of 35% (-2.1° ± 5.0°) (Figure 3).

The disc height increased after surgery ($P < 0.001$) from the preoperative value of 5.4 ± 1.5 mm (range: 2.7 - 8.1 mm) to the postoperative value of 9.3±1.4 mm (range: 7.3 - 12.8 mm) by a correction rate of 72% (3.9 ± 1.6 mm) (Figure 3).

A positive correlation was found between the wedge angle and the axial rotation angle (r = 0.46, P < 0.001, Figure 4).

Effect of LLIF procedure on correction of global deformities

The Cobb angle decreased after surgery (P = 0.035) from the preoperative value of 15.2° ± 9.7° (range 2°–40°) to the postoperative value of 11.6° ± 9.1° (range 0°–37°). The LL increased after surgery (P = 0.041) from the preoperative value of 27.7° ± 18.8° (range −7° to 60°) to the postoperative value of 34.4° ± 17.5° (range -6° to 68°). The SVA decreased after surgery (P < 0.01) from the preoperative value of 72.6 ± 57.8 mm (range -7.5 to 40 mm) to the postoperative value of 42.1 ± 37.8 mm (range -15.9 to 166.1 mm). The PI-LL decreased after surgery (P = 0.017) from the preoperative value of 22.6° ± 16.3° (range -8° to 62°) to the postoperative value of 15.5° ± 15.3° (range -13° to 52°) (Table 2).

Representative case

The patient complained of right lower extremity pain before surgery. We diagnosed L4/5 right foraminal stenosis and performed LLIF. The wedge angle decreased after surgery from the preoperative value of 11.3° to the postoperative value of 4.8° (correction rate 58%). The lordosis angle increased after surgery from the preoperative value of 1.3° to the postoperative value of 5.9° (correction rate 354%). The axial rotation angle decreased after surgery from the preoperative value of 13° to the postoperative value of 9.5° (correction rate 27%). The disc height increased after surgery from the preoperative value of 4.3 mm to the postoperative value of 10.5 mm (correction rate 144%) (Figure 5). Postoperatively, the right leg pain was alleviated.

Discussion

The present study demonstrated that the strong correlations between the wedge angle and the axial rotation angle existed in the patients with lumbar degenerative disease and the LLIF procedure restored the disc height and corrected 3D deformities in three anatomical planes using the patient-specific 3D-CT models created by preoperative and postoperative CT scanning. The 3D analyses of the lumbar alignment allowed accurate quantitative measurements of 3D rotational deformities in the patients with lumbar degenerative disease and the correction of these rotational deformities by the LLIF which is difficult to measure in the two-dimensional plane radiograms.

Longitudinal studies to look at progression of the spinal deformity by evaluating Cobb angle and rotational deformity by such as Nash and Moe's method which determined the grade (0 to IV) reported that Cobb angle increased by more than 10 ° in grade II and III cases in patients with adult spinal deformity who had follow-up for at least 10 years.[3] These studies indicated that the axial rotation is one of the relevant factors of progression of the DLS patients.[8, 9] Korovessis et al. and Ferrero et al. stated that intervertebral disc space asymmetry that occurs, followed by rotatory subluxation, including intervertebral lateral slip and rotation, causes *de novo* degenerative scoliosis as the 3D deformity mechanism of the spine.[10, 11] It is possible that the deformity of the vertebral bodies, the form of the facet joints, the angle of the cage, the position of cage after insertion, the shape of the adjacent intervertebral space, and osteoporosis, among other factors, might be related.[12, 13] The quantitative 3D analysis on the segmental axial rotation using patient-specific 3D models shown in the present study would provide more accurate prediction of future progression of the spinal deformity in DLS. Future longitudinal studies will be warranted to demonstrate the benefit of this technology.

Surgical correction of the combined wedge and rotational deformity is important for improving clinical symptoms derived from intervertebral foramina and spinal canal stenosis. Wiktor et al. reported that they obtained 29.3% rotational correction of DLS by direct vertebral rotation method using pedicle screws and corrective connection devices,[14] but we could find no reports of rotation correction with LLIF. In the present study, we achieved rotational correction of 35% with the LLIF procedure. It should be noted that intentional correction of the axial rotation from the posterior side or dissociated facet joints was not performed in the present study.

In this study, not only was the local lordosis angle increased by LLIF but the global deformity was affected. The LL increased, and the SVA and PI-LL decreased, with the increase in LL large relative to the increase in the local lordosis angle. These improvements in sagittal parameters are unlikely to be the result of local anatomical changes alone. We surmised that they came close to the patient's original posture because the back and leg pain was relieved. The Cobb angle in the coronal plane was also corrected, correlated with the parallel reduction of a single intervertebral disc space. These alterations in the global alignment would produce better clinical results along with the local effects of the single-level correction.

The present study showed the positive correlation between the wedge correction angle and the axial rotation correction angle. Interestingly, this correlation is similar to the correlation between wedge deformation angle and axial rotation deformation angle shown preoperatively with the similar correlation equation. Because only distraction force was applied to restore the disc height and no external torque was applied to correct the axial rotation in the present study, wedge and axial rotational movements during progression of deformity or correction procedure can be described as a "coupled motion."

The coupled motion in lumbar lateral bending has been observed in several studies.[15-17] In lateral bending, the inferior articular process glides superior direction in reference to the superior articular process of the inferior vertebra on the convex side of the spinal curve and opposite direction on the concave side.[18] Schendel et al. reported that lateral bending motion was coupled with axial rotation (i.e. left lateral bending was associated with axial rotation which loads the right facet) and the facet resultant contact force location in left lateral bending was in the same area as that for right axial torsion.[15] The authors suggested that the axial rotation component associated with lateral bending could be partially responsible for facet loading.[15] During correction of the wedge deformity, spinal ligamentotaxis by anterior and posterior longitudinal ligaments may also contribute to the coupled motion.[19, 20]

There are some limitations in our study. We did not evaluate the installation position of the XLIF cage. The position of the cage could affect not only the lordosis angle but also the wedge angle and axial rotation angle. The CT scans used for postoperative evaluation in our study were obtained after both the cage and PPS had been inserted. Therefore, the contribution of correction achieved by in situ PPS fixation cannot be ignored. Because we did not consider facet degeneration, disc degeneration, segmental stiffness, or size or distribution of osteophytes, it is unclear whether the correction effect will be reproducible when this procedure is performed on other patients.

Future studies on 3D geometry and kinematics of the facet joint will be needed to understand the wedge and axial rotational coupled deformation in the patients with lumbar degenerative disease and the coupling effects in correction of the 3D deformities. Evaluation of deformity and/or dislocation of the facet joint may also be needed to predict the reduction effects of the LLIF in the future studies.

Conclusion

The present study demonstrated positive correlations between the wedge deformity and the axial rotational deformity in 28 patients with lumbar degenerative disease who underwent LLIF surgery using patient-specific 3D-CT models. The axial rotational deformity was simultaneously corrected with LLIF only by leveling the intervertebral wedge deformity via cage insertion. The coupled motion caused by the facet joint and ligamentotaxis may contribute to achieve intervertebral correction of both wedge and axial rotational deformities only by inserting a cage during LLIF; however, future studies will be required to understand mechanisms of the coupling effects in correction of the 3D deformities by LLIF.

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Figure 1

A) Eigenvectors of each posterior wall were calculated to determine 3D orientation of the posterior wall. A Cartesian (X-Y-Z) local coordinate system was set on each posterior wall in which an origin was set on a centroid of the posterior wall and orientation was determined by the eigenvectors.

B) The rotations of the superior vertebral body relative to the inferior vertebral body in the adjacent two vertebral bodies were expressed using Eulerian angles. The wedge angle, lordosis angle and axial rotation angle were defined by them in the coronal plane, sagittal plane and axial plane, respectively.

C) Three-dimensional disc height distribution was measured by the least distances between each point of the lower bony endplate of the superior vertebral body and the superior bony endplate of the inferior vertebral body and the mean value of the least distances was determined as the disc height.

Figure 2

A strong positive correlation was found between the wedge angle and the axial rotation angle (r = 0.718, $P < 0.001$) in the patients with lumbar degenerative disease preoperatively.

Figure 3.

The disc height and the lordosis angle increased, while the wedge and axial rotation angles decreased after LLIF.

Figure 4.

A positive correlation was found between the wedge angle and the axial rotation angle ($r = 0.46$, $P < 0.001$) in the patients with lumbar degenerative disease postoperatively.

Figure 5.

These are standing anteroposterior and lateral radiographic images before and after surgery in the representative case. The disc height and the lordosis angle increased, while the wedge and axial rotation angles decreased after LLIF. The Cobb angle and PI-LL decreased, while the LL increased.

Table1.

These are the demographic data of this study group.

Table2.

These are the average values of spinopelvic parameter before and after surgery in this study.

Figure

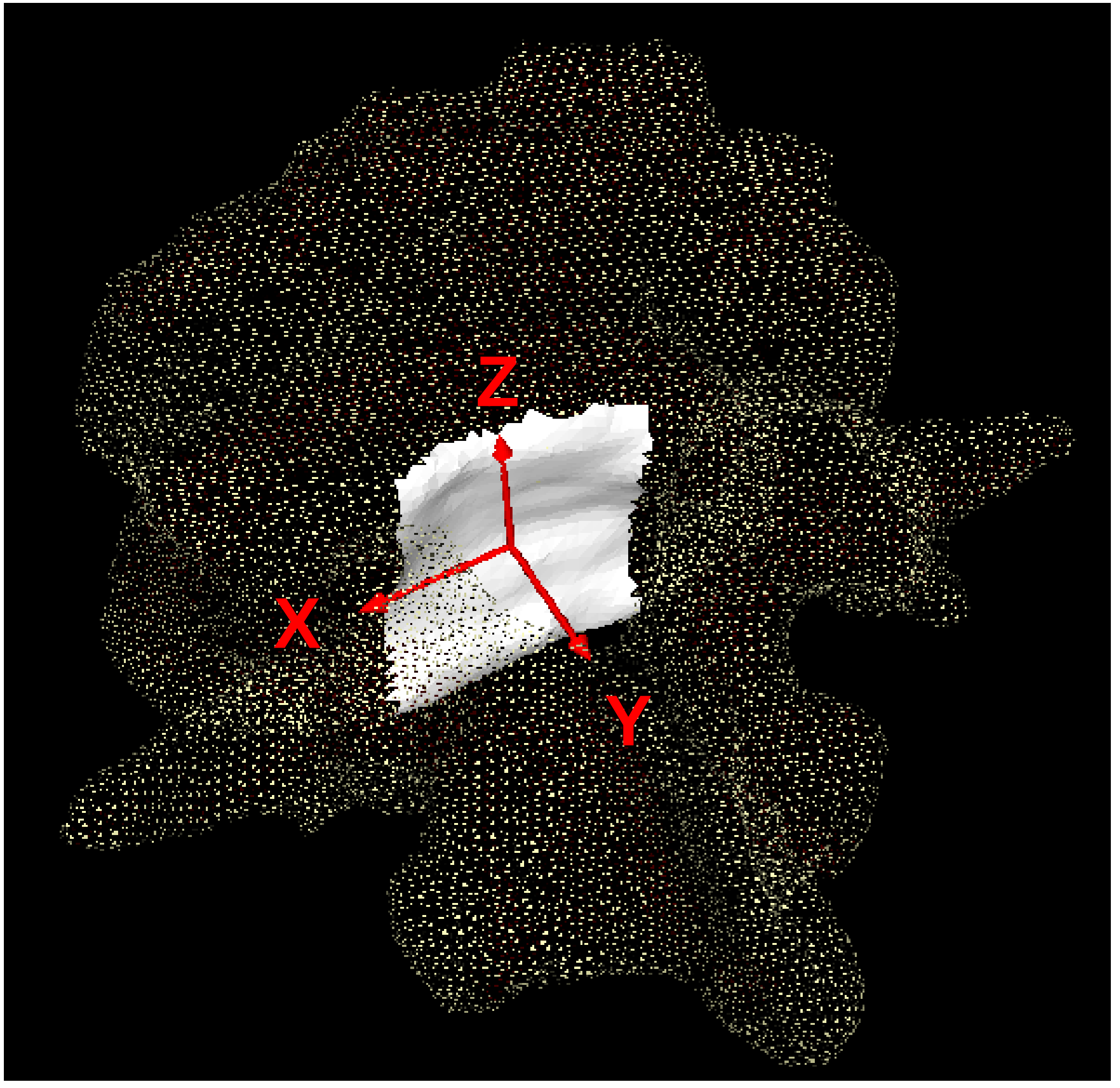


Fig. 1A

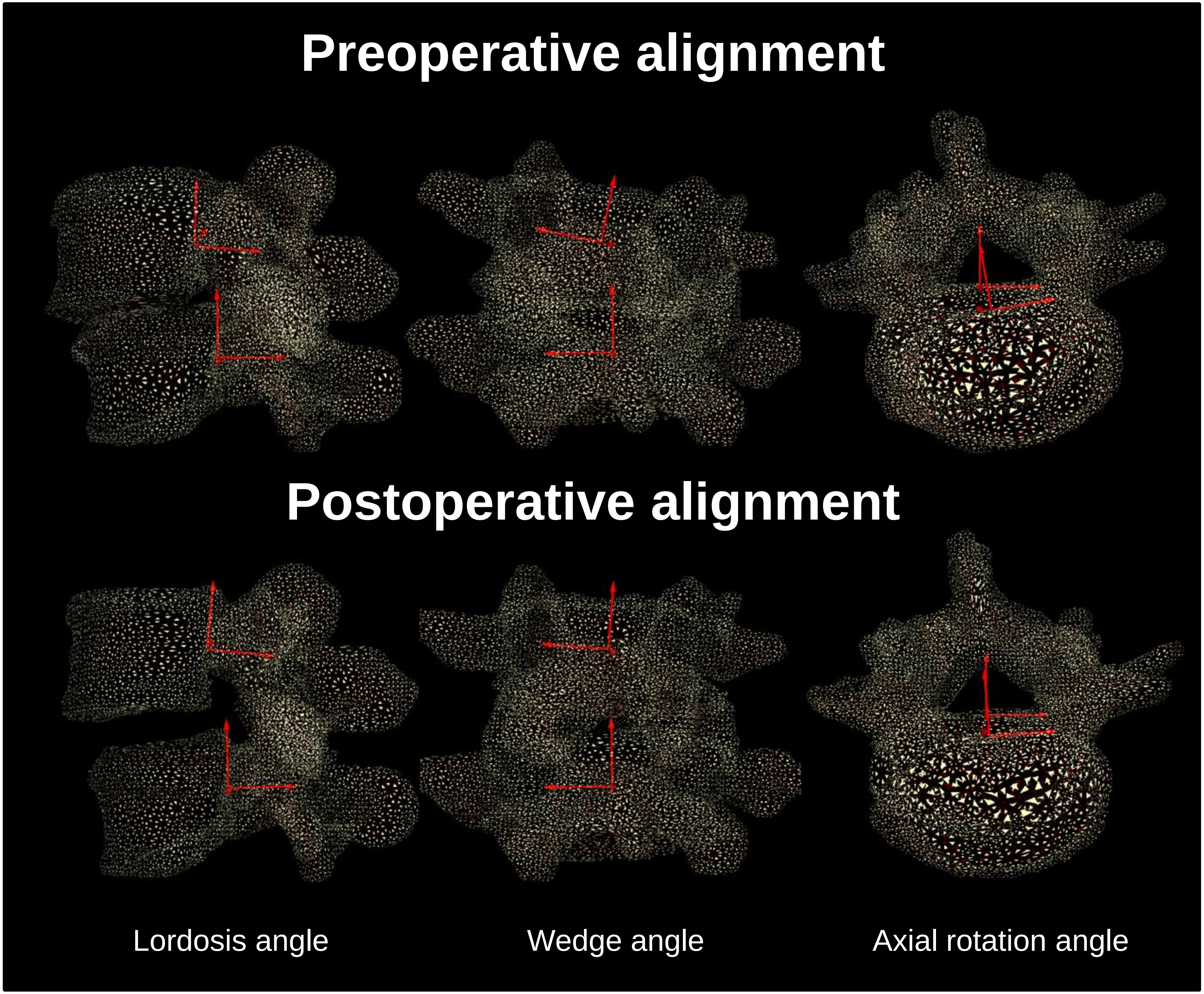
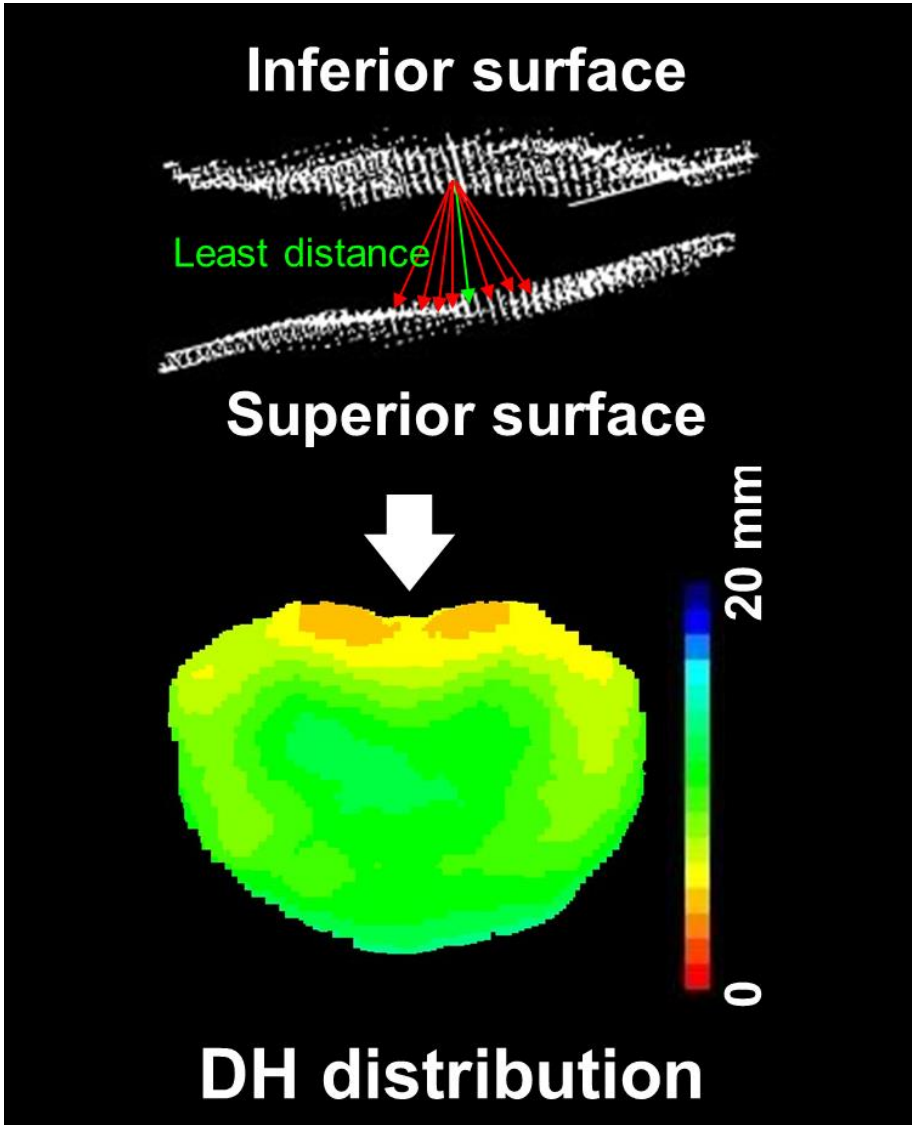
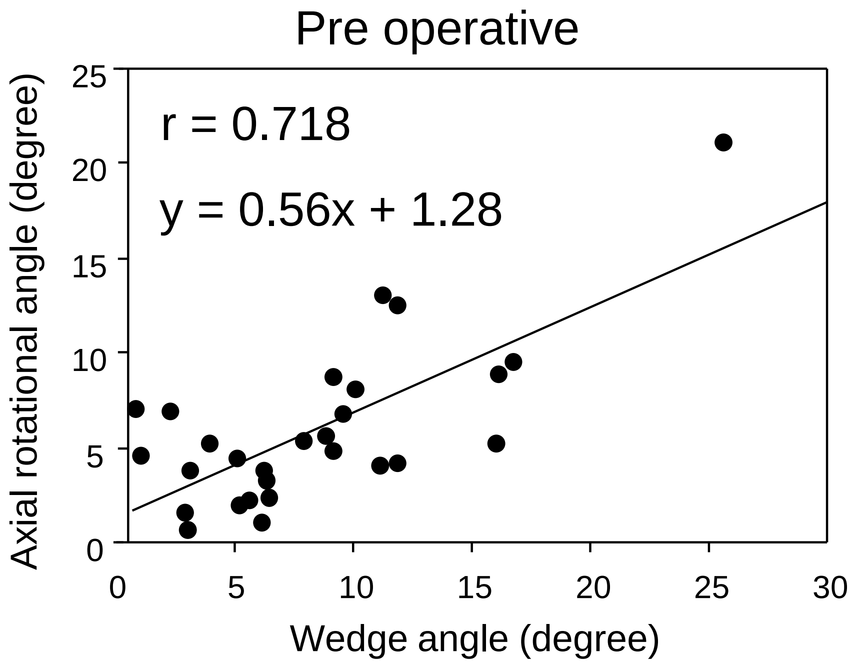

Preoperative alignment
Postoperative alignment
Lordosis angle
Wedge angle
Axial rotation angle

Fig. 1B



Inferior surface
Least distance
Superior surface
20 mm
0
DH distribution

Fig. 1C



Pre operative
r = 0.718
y = 0.56x + 1.28
Axial rotational angle (degree)
Wedge angle (degree)
0
5
10
15
20
25
30

Fig. 2

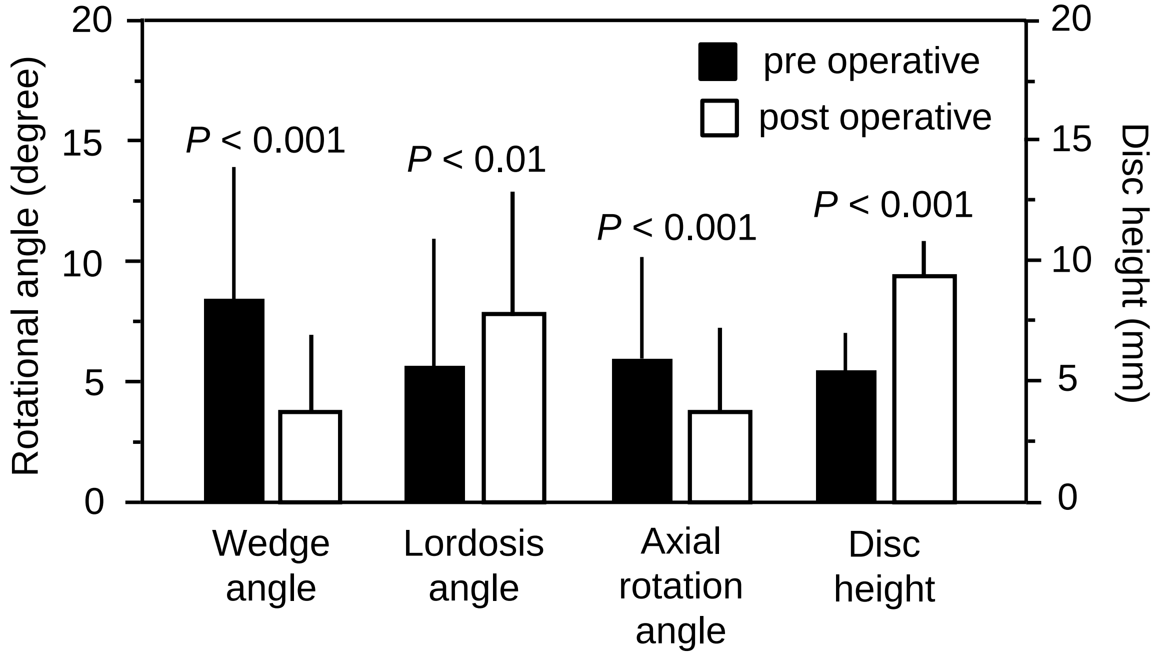

20
15
10
5
0
Rotational angle (degree)
20
15
10
5
0
Disc height (mm)
pre operative
post operative
P < 0.001
P < 0.01
P < 0.001
P < 0.001
Wedge angle
Lordosis angle
Axial rotation angle
Disc height

Fig. 3

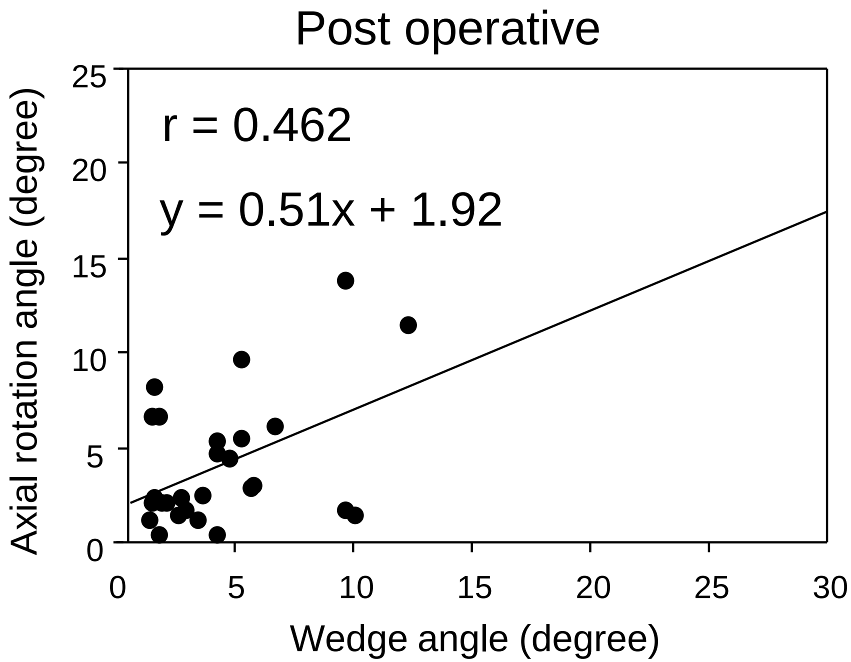

Post operative
r = 0.462
y = 0.51x + 1.92
Axial rotation angle (degree)
Wedge angle (degree)
0
5
10
15
20
25
30

Fig. 4

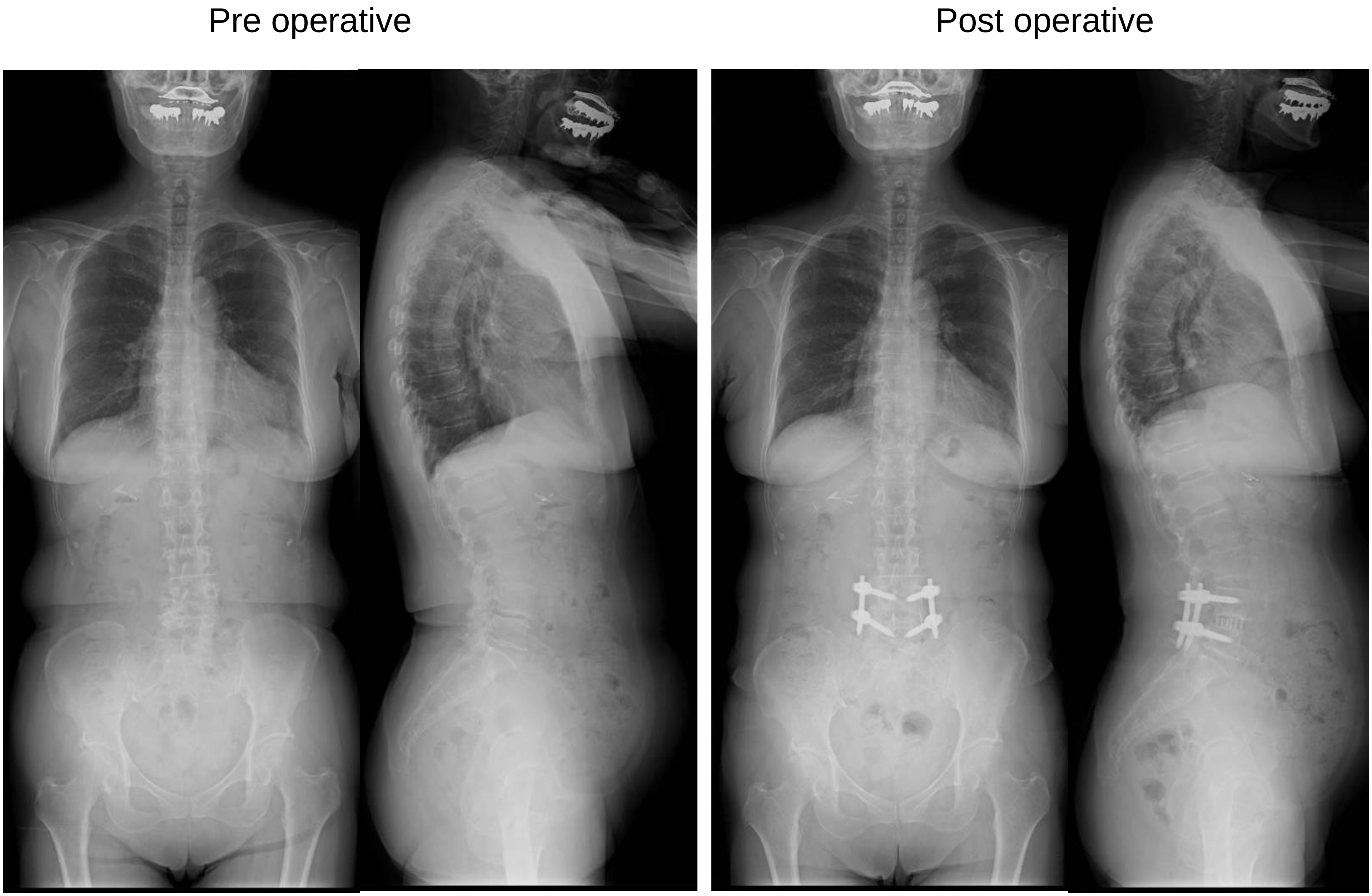


Fig. 5

	Average (n=28)
Age	69.5 ± 9.2
BMI	23.9 ± 3.2

		Number
Sex	male	11
	female	17
Disease	spondylosis	4
	scoliosis	16
	spondylolisthesis	8

Table. 1

	Pre operative	Post operative	P value
Cobb angle	15.2° ± 9.7°	11.6° ± 9.1°	0.035
LL	27.7° ± 18.8°	34.4° ± 17.5°	0.041
TK	25.0° ± 11.9°	24.8° ± 12.8°	0.452
SS	24.8° ± 10.4°	26.8° ± 7.6°	0.169
PT	25.6° ± 8.2°	23.2° ± 7.3°	0.074
PI	50.3° ± 8.2°	50.0° ± 8.3°	0.413
SVA	72.6 ± 57.8mm	42.1 ± 37.8mm	< 0.01
PI-LL	22.6° ± 16.3°	15.5° ± 15.3°	0.017

Table. 2

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Disclosure of potential conflicts of interest

Authors must disclose all relationships or interests that could have direct or potential influence or impart bias on the work. Although an author may not feel there is any conflict, disclosure of all relationships and interests provides a more complete and transparent process, leading to an accurate and objective assessment of the work. Awareness of real or perceived conflicts of interest is a perspective to which the readers are entitled. This is not meant to imply that a financial relationship with an organization that sponsored the research or compensation received for consultancy work is inappropriate. For examples of potential conflicts of interests *that are directly or indirectly related to the research please* visit:
http://www.springer.com/gp/authors-editors/journal-author/journal-author-helpdesk/publishing-ethics/14214

All authors of papers submitted to European Spine Journal
[*include name of journal*] must complete this form and disclose any real or perceived conflict of interest.

Please complete one form per author. The corresponding author collects the conflict of interest disclosure forms from all authors. The corresponding author will include a summary statement that reflects what is recorded in the potential conflict of interest disclosure form(s). Please check the Instructions for Authors where to put the statement which may be different dependent on the type of peer review used for the journal. Please note that you cannot save the form once completed. Please print upon completion, sign, and scan to keep a copy for your files.
The corresponding author should be prepared to send potential conflict of interest disclosure form if requested during peer review or after publication on behalf of all authors (if applicable).

☑ I have no potential conflict of interest.

Category of disclosure	Description of Interest/Arrangement

Article title Coupling Effects in Correction of Three-dimensional Deformity in Degenerative Lumbar Scoliosis by Lateral Lumbar Interbody Fusion

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Are you the corresponding author? ☐ Yes ☑ No

Herewith I confirm that the information provided is accurate.

Author signature Hiroto Yamaguchi Date April 21, 2019