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RESEARCH ARTICLE

Biomechanical Comparison of Different Surgical Approaches for the Treatment of Adjacent Segment Diseases after Primary Transforaminal Lumbar Interbody Fusion: A Finite Element Analysis

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Background and objective: Adjacent segment disease (ASD) is a well-known complication after interbody fusion. Revision surgery is necessary for symptomatic ASD to further decompress and fix the affected segment. However, no optimal construct is accepted as a standard in treating ASD. The purpose of this study was to compare the biomechanical effects of different surgical approaches for the treatment of ASD after primary transforaminal lumbar interbody fusion (TLIF).

Methods: A finite element model of the L1-S1 was conducted based on computed tomography scan images. The primary surgery model was developed with a single-level TLIF at L4-L5 segment. The revision surgical models were developed with anterior lumbar interbody fusion (ALIF), lateral lumbar interbody fusion (LLIF), or TLIF at L3-L4 segment. The range of motion (ROM), intradiscal pressure (IDP), and the stress in cages were compared to investigate the biomechanical influences of different surgical approaches.

Results: The results indicated that all the three surgical approaches can stabilize the spinal segment by reducing the ROM at revision level. The ROM and IDP at adjacent segments of revision model of TLIF was greater than those of other revision models. While revision surgery with ALIF and LLIF had similar effects on the ROM and IDP of adjacent segments. Compared among all the surgical models, cage stress in revision model of TLIF was the maximum in extension and axial rotation.

Conclusion: The IDP at adjacent segments and stress in cages of revision model of TLIF was greater than those of ALIF and LLIF. This may be that direct extension of the surgical segment in the same direction results in stress concentration.

Key words: Adjacent segment degeneration; Biomechanical; Finite element; Lumbar spine; Revision surgery

Introduction

Lumbar interbody fusion is used to treat lumbar spine diseases, such as spinal stenosis and spondylolisthesis.[1] Transforaminal lumbar interbody fusion (TLIF) is a common surgical procedure of lumbar interbody fusion, first introduced by Harms and Jeszenszky.[2] TLIF is recognized as

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a safe and effective technique with lower blood loss and complication rates.[3,4] However, adjacent segment disease (ASD) is a common problem following TLIF. A previous study reported that the annual incidence for the development of symptomatic ASD following lumbar fusion surgery ranges from 0.6% to 3.9%.[5] In a retrospective study of 159 patients who underwent TLIF, 55 patients developed symptomatic ASD and underwent a revision surgery.[6] The mean time between index and revision surgery was 26.2 months. In addition, ASD is more likely to occur in the upper segment of the original surgery.[6,7]

Revision surgery was necessary for symptomatic ASD to fix the affected segment.[8–10] For revision of TLIF, the second surgery can be performed using a variety of approaches, such as posterior, direct anterior, or lateral.[11] However, no optimal surgical protocol is considered the standard for treating ASD. A traditional approach is to perform revision surgery by replacing prior rods with longer rods to extend the fusion levels.[12] However, this method requires removal of a large amount of soft tissue to expose the previously implanted constructs, which increases blood loss and postoperative pain. An alternative strategy for revision surgery is to select a different approach to the spine. Anterior lumbar interbody fusion (ALIF) approaches the spine through the abdomen rather than the back, avoiding spinal muscle dissection by simply contracting the abdominal muscles and peritoneal contents.[13] A cadaveric investigation demonstrated that revision ALIF maintained biomechanical stability of TLIF.[14] Lateral lumbar interbody fusion (LLIF) can also reduce spinal muscle dissection by using a cage that lays across the vertebral endplates inserted laterally. A previous retrospective study suggested that LLIF is an attractive technique for ASD of TLIF with reduced blood loss and complications.[15]

Due to the limited number of revision cases after TLIF, the comparison of different revision procedures has been less studied. Recently, finite element (FE) analysis has been widely used to evaluate the biomechanical effects of different spine surgeries.[16,17] FE analysis can accurately simulate different surgical methods, and has unique advantages in the comparison of revision surgery. In the present study, FE models of three revision surgeries (ALIF, LLIF, TLIF) based on L4-L5 TLIF were conducted. The aim of this study was to: (i) describe ALIF, LLIF and TLIF for the treatment of ASD after primary TLIF; (ii) evaluate the efficacy and feasibility of different surgical approaches for the treatment of ASD after primary TLIF; and (iii) compare the biomechanical effects of different surgical approaches for the treatment of ASD after primary TLIF.

Materials and Methods

Construction of Intact Lumbar Model (L1-S1)

The finite element model of the intact lumbar spine used in this study was developed and validated in our previous study.[18] In brief, an accurate 3-dimensional finite element model of an L1-S1 segment was developed using computed tomography images with slice thickness of 0.625 mm from a healthy male volunteer aged 29 years. The data were imported into Mimics Research 20.0 software (Materialise, Leuven, Belgium) to reproduce the geometric structure of the vertebrae. The solid model was generated in Solidworks software (version 2017; SolidWorks Corp, Concord, MA). Biomechanical evaluation of the finite element model was performed using ANSYS (ANSYS Ltd., Canonsburg, PA, USA). The lumbar model included cortical bone, cancellous bone, endplates, intervertebral discs (IVD), and seven types of ligaments. The IVD consisted of annulus fibrosus and nucleus pulposus, and it was considered as a hyperplastic material as referred to previous studies.[19,20] The ligaments were established using a nonlinear tension-only spring element. The material properties of FE model were listed in Table 1.

Primary Surgical Model of L4-L5 TLIF

TLIF at L4-L5 segment is recognized as the primary surgery. To simulate the model of TLIF (Fig. 1A), part of the left facet joint, ligamentum flavum, part of the annulus fibrosus, and nucleus pulposus were removed. L4-L5 segment was fixed with a screw-rod system. A polyetheretherketone (PEEK) cage filled with cancellous bone was inserted into the L4-L5 intervertebral space, and solid fusion was adopted between the cage and vertebral bodies. The screws and rods were made of titanium alloy (Ti6Al4V).

Revision Surgical Model

According to previous study, ASD is more likely to occur in the upper segment of the original surgery.[6,7] Therefore, revision surgical models of ALIF, LLIF, and TLIF at L3-L4 segment were conducted, respectively. To simulate the revision surgical model of L3-L4 TLIF (Fig. 1B), bilateral longer rods

TABLE 1 Material properties of the spinal structures

Component/materials	Young's modulus E(MPa)	Poisson's ratio
Cortical bone	12,000	0.3
Cancellous bone	100	0.2
Posterior element	3500	0.25
Endplate	1000	0.3
Nucleus pulposus	1	0.499
Annulus	1.75	0.45
Annulus fiber	450	0.3
Anterior longitudinal ligament	7.8	0.3
Posterior longitudinal ligament	10	0.3
Ligamentum flavum	15	0.3
Capsular ligament	7.5	0.3
Interspinous ligament	8	0.3
Supraspinous ligament	8	0.3
Intertransverse ligament	10	0.3
PEEK	3600	0.3
Ti6Al4V	110,000	0.3

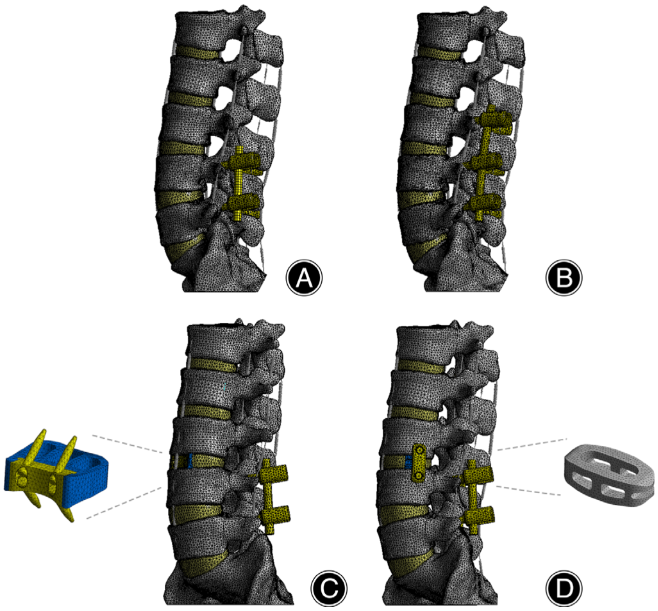

FIGURE 1 FE models of primary or revision surgery. (A) Primary surgical model of L4-L5 TLIF. (B) Revision surgical model of L3-L4 TLIF. (C) Revision surgical model of L3-L4 ALIF. (D) Revision surgical model of L3-L4 LLIF.

from L3 to L5 were used to replace the prior rods, and a TLIF cage was inserted into the L3-L4 intervertebral space. To simulate the revision surgical model of L3-L4 ALIF (Fig. 1C), a stand-alone PEEK cage (SynFix; Synthes Spine Inc., PA, USA) was used and fixed with an anterior metal plate (Ti6Al4V) and four screws (Ti6Al4V). The SynFix cage is characterized as follows: 38 mm length, 30 mm width, 13.5 mm height, and lordotic angulation equal to 12°. The anterior longitudinal ligaments and nucleus pulposus were removed, and 2/3 of the annulus fibrosus was resected. To simulate the revision surgical model of L3-L4 LLIF (Fig. 1D), a laterally-inserted PEEK cage (48 mm length, 22 mm width, 9 mm height) was constructed according to a commercially-available LLIF cage (DePuy Synthes GmbH, Waldenburg, Switzerland). A lateral plate and two screws were used for fixation. The cages of all revision surgical models were filled with cancellous bone, and solid fusion was assumed between the cage and vertebral bodies. Previous studies have reported that the lumbar curvature may influence the development of ASD.[21,22] Therefore, during construction of revision surgery models, we tried to avoid the influence of any surgical device on lumbar curvature. The curvatures of L3-L5 segments of re-ALIF, re-LLIF and re-TLIF were 25.1°, 24.4° and 24.8°, which had no significant difference.

Boundary and Loading Conditions

All models were fixed at the inferior surface of the sacrum. A 400-N vertical axial preload was imposed on the superior surface of L1 and a 10-N·m moment was applied on the L1 superior surface along the radial direction to simulate spinal motions, including flexion, extension, bending, and torsion.[23,24] The range of motion (ROM), intradiscal pressure (IDP), and stress in cages were compared to investigate biomechanical influences of different surgical approaches. Segmental ROM means the change of angle between the upper edges of two adjacent vertebrae. IDP and the stress in cages mean the maximum von Mises stress distributed on IVD or cages.

Results

ROM

A comparison of ROM of different revision models is shown in Fig. 2. Compared to the primary surgery model, the ROM at revision segment (L3-L4) was reduced in each model after revision surgery was performed. At the adjacent segments (L2-L3, L5-S1), the ROM increased after revision surgery compared with those in the primary surgery model. In these revision surgical models, revision with L3-L4 TLIF resulted in a greater increase in ROM of adjacent segments, especially in extension, and left axial rotation. In addition, revision with ALIF and LLIF had similar effects on the ROM of adjacent segments.

IDP

The IDP of different models is demonstrated in Fig. 3 and Table 2. The intervertebral disc of L3-L4 and L4-L5 was partially resected, the IDP of them was not obtained. The IDP at the adjacent segments increased in all revision surgery models compared with those in the primary surgery model. The values of IDP of the revision model of ALIF under all directions were similar to those of revision mode l of LLIF. At the segment of L2-L3, the values of IDP of the revision model of TLIF was greater than those of other revision models in almost all loading directions. The IDP of revision model of TLIF of flexion, extension, left lateral bending, right lateral bending, left axial rotation and right axial rotation at the segment of L2-L3 were 1.19 MPa, 1.49 MPa, 1.42 MPa, 1.40 MPa, 1.53 MPa, and 1.51 MPa, respectively. While at the segment of L5-S1, the values of IDP of the revision model of TLIF had great increase in flexion (1.86 MPa) and extension (2.87 MPa). The stress distribution in intervertebral disc at L2-L3 and L5-S1 segments of different surgical approaches in flexion and extension motion are shown in Fig. 4.

The Stress in Cages

The comparison of the stress distributed on cages between different revision models is shown in Fig. 5 and Table 3. Compared with all the surgical models, the maximum stress in cages at L3-L4 and L4-L5 segments was found in the revision model of TLIF, especially in extension and axial rotation. The maximum stress in cages in the revision model of TLIF in extension motion at L3-L4 and L4-L5 segments was 21.77 MPa and 22.54 MPa, respectively. In lateral bending,

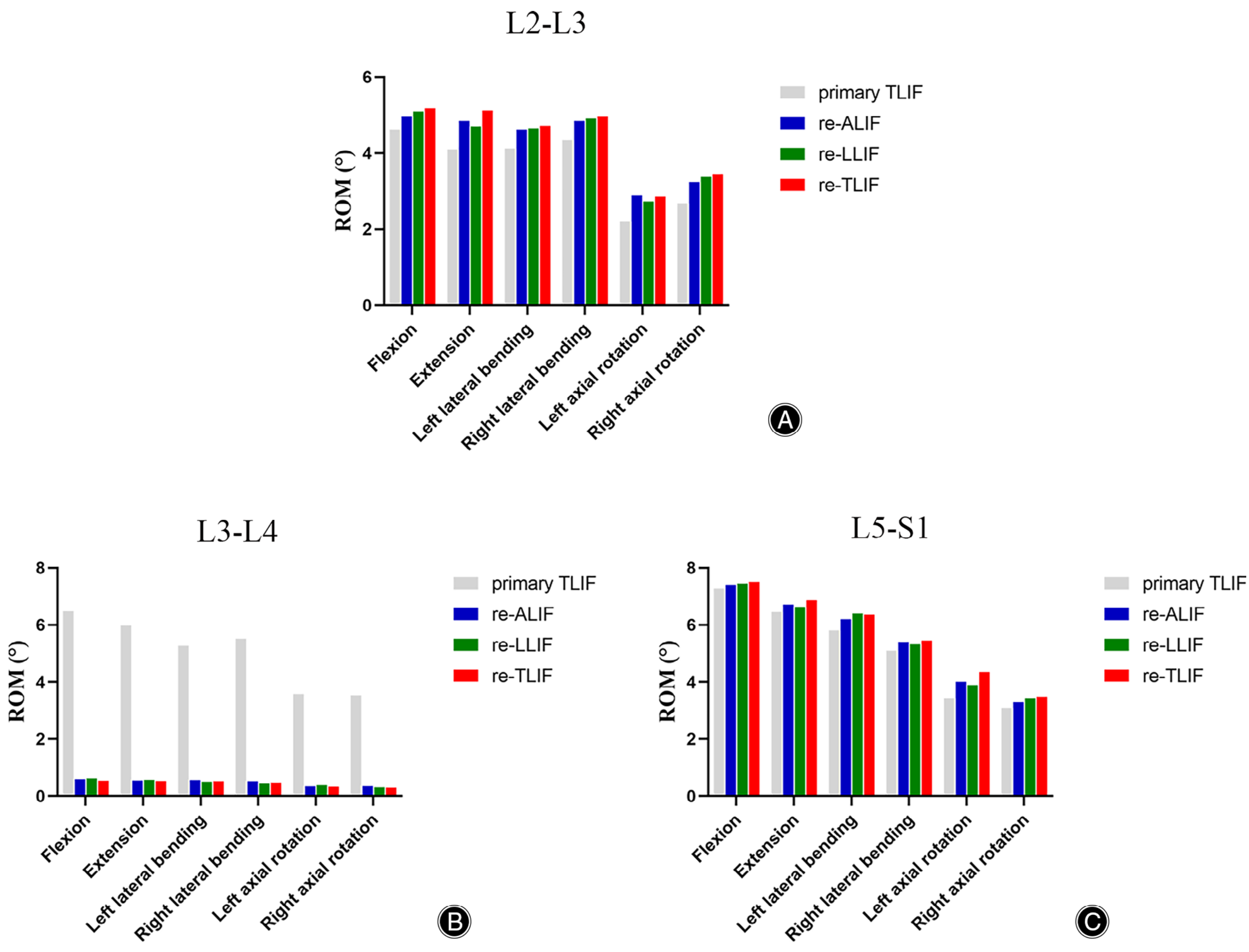

FIGURE 2 Comparison of ROM of different revision models. (A) ROM at L2-L3 segment. (B) ROM at L3-L4 segment. (C) ROM at L5-S1 segment.

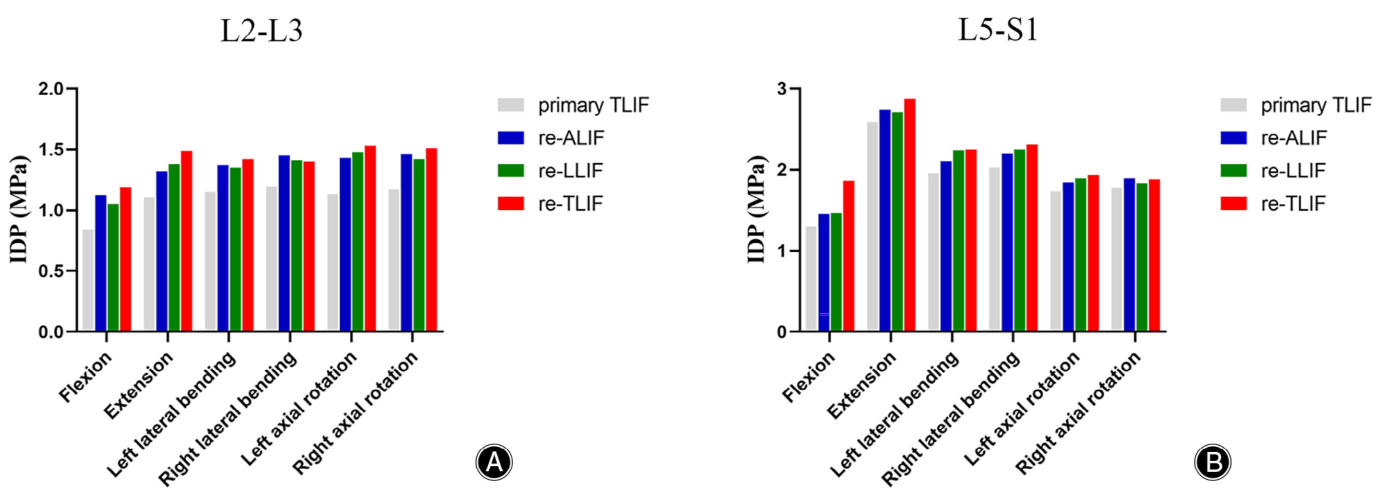

FIGURE 3 Comparison of IDP at adjacent segments of different revision models. (A) IDP at L2-L3 segment. (B) IDP at L5-S1 segment.

TABLE 2 Comparison of IDP at adjacent segments of different revision models (Unit: MPa)

	L2-L3				L5-S1			
	Primary-TLIF	Re-ALIF	Re-LLIF	Re-TLIF	Primary-TLIF	Re-ALIF	Re-LLIF	Re-TLIF
Flexion	0.84	1.12	1.05	1.19	1.30	1.45	1.46	1.86
Extension	1.10	1.32	1.38	1.49	2.59	2.74	2.71	2.87
Left lateral bending	1.54	1.37	1.35	1.42	1.96	2.10	2.24	2.25
Right lateral bending	1.20	1.45	1.41	1.40	2.03	2.20	2.25	2.31
Left axial rotation	1.13	1.43	1.48	1.53	1.74	1.84	1.89	1.93
Right axial rotation	1.17	1.46	1.42	1.51	1.78	1.89	1.83	1.88

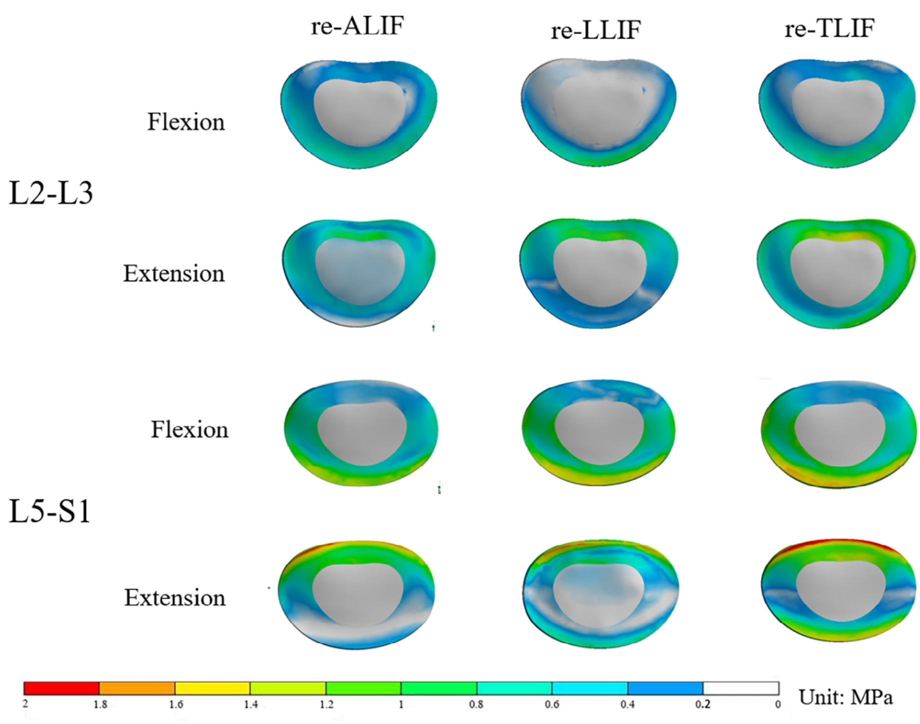

FIGURE 4 The stress distribution in intervertebral disc at L2-L3 and L5-S1 segments of different surgical approaches in flexion and extension motion.

the maximum stress in cages was found in the revision model of LLIF, especially in right lateral bending of the L3-L4 segment (17.26 MPa). The stress distribution in cages at L3-L4 and L4-L5 segments of different surgical approaches in flexion and extension motion are shown in Fig. 6.

Discussion

In this study, three revision surgical models of ALIF, LLIF, and TLIF at the L3-L4 segment were constructed based on the L4-L5 TLIF model to compare the biomechanical effects of different surgical approaches for the treatment of ASD after primary TLIF. The results indicated that all three surgical approaches can stabilize the spinal segment by reducing ROM at the revision level. However, the ROM and IDP at adjacent segments of the revision model of TLIF was greater than those of other revision models. While revision surgery with ALIF and LLIF had similar effects on the ROM and IDP of adjacent segments. Compared with all surgical models, cage stress in the revision model of TLIF was the greatest in extension and axial rotation.

Different Surgical Approaches for Treating ASD

ASD following the primary fusion surgery is a common complication in clinical practice.[25–27] Further decompressing and fusing the affected segment was necessary for treating ASD.[8] According to previous studies, anterior, lateral and posterior approaches are all viable options.[15,28] However, there is no consensus on which approach is more appropriate for the treatment of ASD after primary TLIF. In this study, our results indicated that different surgical approaches can achieve similar biomechanical stability of the revision segment. Extending the prior fusion level is a commonly used strategy for revision surgery. A previous study designed four types of revision surgery for ASD after TLIF by replacing or preserving the primary implants, and found that the biomechanical effects were approximately identical

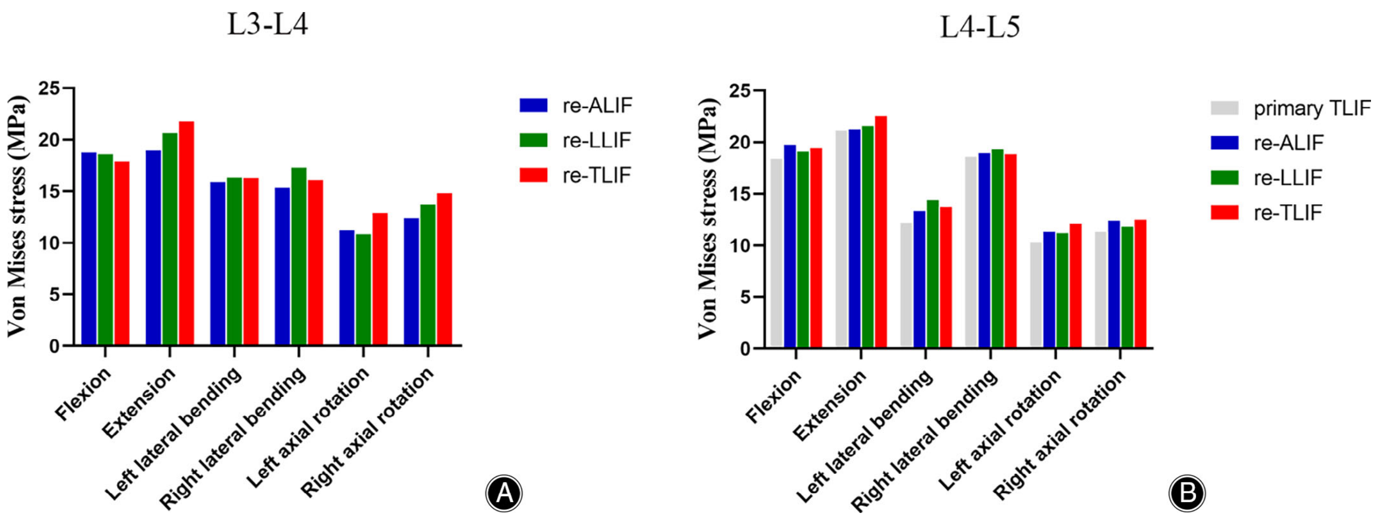

FIGURE 5 Comparison of the maximum von Mises stress distribution on cages between different revision models. (A) Stress in cages at the L3-L4 segment. (B) Stress in cages at the L4-L5 segment.

TABLE 3 Comparison of the maximum von Mises stress distribution on cages between different revision models (Unit: MPa)

	L3-L4			L4-L5			
	Re-ALIF	Re-LLIF	Re-TLIF	Primary-TLIF	Re-ALIF	Re-LLIF	Re-TLIF
Flexion	18.76	18.60	17.91	18.41	19.76	19.12	19.41
Extension	18.94	20.63	21.77	21.11	21.22	21.62	22.54
Left lateral bending	15.91	16.33	16.27	12.19	13.32	14.41	13.72
Right lateral bending	15.32	17.26	16.09	18.59	18.94	19.31	18.85
Left axial rotation	11.22	10.85	12.88	10.32	11.33	11.20	12.11
Right axial rotation	12.41	13.71	14.80	11.33	12.41	11.81	12.53

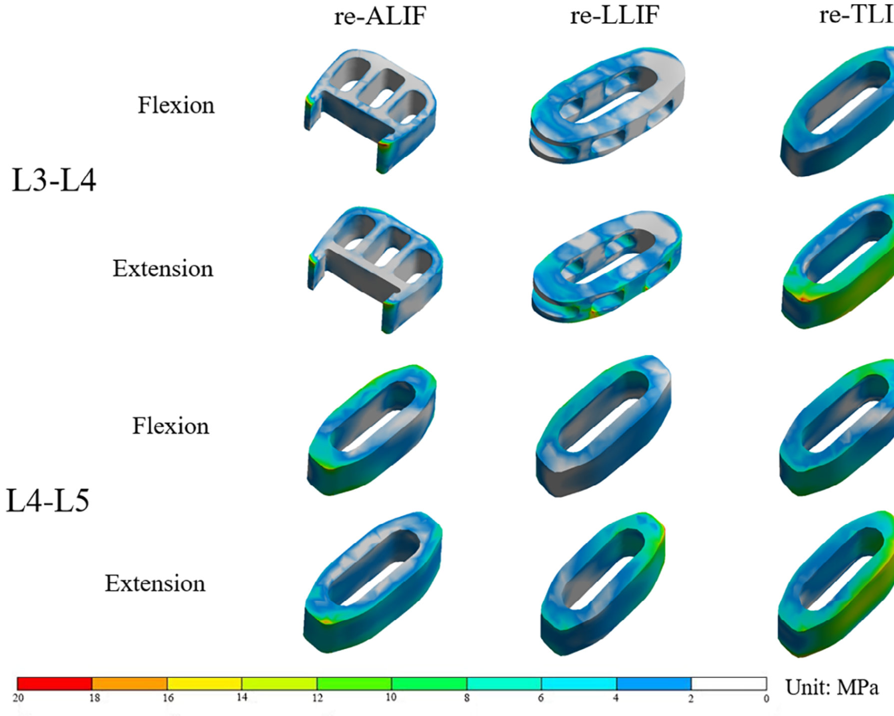

FIGURE 6 The stress distribution in cages at the L3-L4 and L4-L5 segments of different surgical approaches in flexion and extension motion.

among them.[29] Another study reported that patients undergoing revision fusion *via* TLIF or ALIF reported similar 1-year postoperative mean outcomes.[28] For revision surgery of LLIF, a finite element study demonstrated that the lateral cage alone cannot provide adequate ROM restriction of the fusion segment and supplementary fixation is required to achieve favorable biomechanical stability,[30] which is similar to our results.

Comparison between Different Surgical Approaches for ASD

Although there are numerous surgical approaches for revision surgery, the comparison between different surgical methods is a question worth studying. Revision lumbar fusions were reported to have wide variation in success rates, ranging from 12% to 82%.[31] A retrospective analysis found that patients who underwent revision surgeries were more likely to have worse clinical outcomes.[32] Our results indicated that the ROM and IDP at adjacent segments of the revision model of TLIF was greater than those of other revision models, which may contribute to the recurrence of ASD. In addition, cage stress in the revision model of TLIF was maximum, especially in extension and axial rotation. This may be that direct extension of the surgical segment in the same direction results in stress concentration. ALIF and LLIF allow the use of larger cages, which can realize a more favorable stress sharing effect.[33,34] Furthermore, the combined anterior–posterior or lateral-posterior approach facilitates stress dispersion. Other studies also reported that ALIF and LLIF did not impose a significant burden on adjacent segments and cages.[14,30]

Clinical practice also needs to be considered when choosing the approach of revision surgery. Revision with TLIF needs to reopen the surgical scar tissue and replace the rods, resulting in a higher risk of dural violations and cerebrospinal fluid leakage.[35] However, the anterior and lateral approaches can avoid the separation of previous scar tissue and has the advantage of being minimally invasive. Posterior spinal elements and facet joint capsules are not disrupted through an anterior or lateral approach.[36,37] Furthermore, most ASD occurs proximal to this location and thus would involve revision surgery at the mid or high lumbar segments.[6,7] Therefore, anterior and lateral approaches are more particularly suited for treating lumbar ASD since the majority of primary lumbar fusions occur at the L3–S1 level. A higher segment can reduce the occurrence of neurological complications associated with anterior or lateral surgery.

Limitations

There are several limitations in this study. First, some simplifications were carried out in the model. For example, cancellous bone was assumed as a solid structure, which may affect the stress distribution. Second, only three revision approaches were considered in this study, and the biomechanical effect of other revision approaches remains to be further studied. Nevertheless, these are the most commonly adopted options. Furthermore, muscles and other soft tissue were not constructed in the models, which may affect the validation of these lumbar spine models. Nonetheless, this study shows that the anterior and lateral approaches are more suitable for treating ASD after primary TLIF. In addition, more accurate FE modeling and clinical studies are needed to explore the effect of different surgical methods in the future.

Conclusion

In conclusion, ALIF, LLIF or TLIF can stabilize the revision level after primary lumbar interbody fusion. However, the IDP at adjacent segments and stress in cages of the revision model of TLIF was greater than those of other revision models, while ALIF and LLIF did not impose a significant burden on adjacent segments and cages. This may be that direct extension of the surgical segment in the same direction results in stress concentration. Furthermore, the biomechanical results of this study may not fully represent the real situation. Further clinical investigations are necessary to assess the effects of different revision approaches for the treatment of ASD after primary lumbar interbody fusion.

Author Contributions

WCK and TZ designed the study, analyzed the data, and wrote the manuscript. BJW, WBH, and KW participated in the design of the study and analyzed the data. CY and JPYC helped in writing the manuscript, and instructed on the surgical technique. All authors read and approved the final manuscript.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

Ethics Statement

The studies involving human participants were reviewed and approved by The Ethics Committee of Union Hospital, Tongji Medical College, Huazhong University of Science and Technology (S.0469). Written informed consent was obtained from the volunteer.

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