Biomechanical Analysis of Lateral Lumbar Interbody Fusion Constructs with Various Fixation Options: Based on a Validated Finite Element Model

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BACKGROUND: Lateral lumbar interbody fusion using cage supplemented with fixation has been used widely in the treatment of lumbar disease. A combined fixation (CF) of lateral plate and spinous process plate may provide multiplanar stability similar to that of bilateral pedicle screws (BPS) and may reduce morbidity. The biomechanical influence of the CF on cage subsidence and facet joint stress has not been well described. The aim of this study was to compare biomechanics of various fixation options and to verify biomechanical effects of the CF.

METHODS: The surgical finite element models with various fixation options were constructed based on computed tomography images. The lateral plate and posterior spinous process plate were applied (CF). The 6 motion modes were simulated. Range of motion (ROM), cage stress, endplate stress, and facet joint stress were compared.

RESULTS: For the CF model, ROM, cage stress, and endplate stress were the minimum in almost all motion modes. Compared with BPS, the CF reduced ROM, cage stress, and endplate stress in all motion modes. The ROM was reduced by more than 10% in all motion modes except for flexion; cage stress and endplate stress were reduced more than 10% in all motion modes except for rotation-left. After interbody fusion, facet joint stress was reduced substantially compared with the intact conditions in all motion modes except for flexion.

CONCLUSIONS: The combined plate fixation may offer an alternative to BPS fixation in lateral lumbar interbody fusion.

INTRODUCTION

Lumbar interbody fusion has been used in the treatment of lumbar disease such as spondylolisthesis, trauma, and degenerative disc degeneration. Successful clinical outcomes depend on fusion healing. The best opportunity for healing may be the anterior interbody fusion, with better loading of the graft and the largest surface area for fusion.¹⁴ Laterally inserted interbody cages significantly decrease range of motion (ROM) compared with other cages.⁵⁻⁸ The interbody cage fusion improves the loading capacity of the anterior column.⁵⁻⁸ To achieve effective fusion with an interbody cage, supplemented internal fixation often is used. The supplemental fixation favorably influences the healing of the lumbar fusion.⁴

It was known that some factors may affect the risk of cage subsidence, such as fusion constructs, bone quality of vertebral trabecular and endplate, and preparation of endplate. According to the existing literature, the biomechanical effects of various fixation methods on subsidence are not understood fully. Bilateral pedicle...
screw (BPS) fixation has been used widely to supplement interbody cage because it can provide multiplanar stability.\textsuperscript{5,9-11} It may be not negligible to account for one of the primary advantages of pedicle screw fixation, which is for compression dorsal to the instantaneous axis of rotation to increase segmental lordosis.\textsuperscript{5,9-11} However, the fixation of BPS requires an additional posterior procedure, which may increase risk and morbidity of complications.\textsuperscript{12-16}

Compared with BPS, lateral plate (LP) fixation and spinous process plate (SPP) fixation have similar advantages of minimally invasive surgery, such as single-position lateral procedure, shorter operative times, and less blood loss. Recent studies have indicated that both of the fixation options could provide lumbar stability\textsuperscript{5,6,17,18} and reduce morbidity.\textsuperscript{19-21} In the previous in vitro study, Fogel et al.\textsuperscript{4} proposed combined constructs with lateral and posterior plate fixation, which could provide stability similar to BPS fixation. However, the influence of the combined fixation on cage subsidence and facet joint stress (FJS) has not been investigated.

Using a finite element (FE) model to systematically study the biomechanical effects of various fixation options may be valuable. Further information to be determined is the influence of various fixation options on the subsidence at surgical level, as well as damage to the adjacent levels induced by the increased stiffness in the index disc space associated with the interbody cage and supplemented fixation options. The aim of this study was to investigate the biomechanical properties of cage subsidence and FJS with lumbar fusion constructs with various fixation options using finite element analysis (FEA) and to verify the biomechanical effects of the combined fixation.

**MATERIALS AND METHODS**

The FE model of the intact lumbar spine employed in this study was developed and validated in our previous study.\textsuperscript{22} Computed tomography images of intact lumbar spine with intervals of 0.7 mm were obtained from a 36-year-old woman (weight 52 kg, height 158 cm, excluded from lumbar disease based on visual and radiographic examination). A total of 432 computed tomography images were imported into Mimics (Materialise Inc., Leuven, Belgium). The 3-dimensional geometry structure and the mesh structure were constructed by the use of Mimics and Hypermesh (Altair Technologies Inc., Fremont, California, USA), respectively. The mesh model was imported into Abaqus (Simulia Inc, Providence, Rhode Island, USA) to perform FEA. The computer for the simulation is ThinkStation (Lenovo, Beijing, China) configured with 64 GB memory and 24 processors.

**Figure 1** shows the FE model of lumbar spine L1—L5. The vertebral body was composed of cancellous bone, cortical bone, and posterior bone. The intervertebral disc was composed of nucleus pulposus and annulus fibrosus. The model included 7 ligaments: anterior longitudinal ligament, posterior longitudinal ligament, ligamenta flava, interspinal ligament, supraspinal ligament, intertransverse ligament, and capsular ligament. The cortical bone was 1.0 mm thick, and the endplate was 0.5 mm thick.\textsuperscript{11} All the ligaments were modeled with tension-only truss elements (2-node 3-dimensional truss element). The FE model was meshed using the 3-dimensional tetrahedral elements except for the ligaments. There were 195,533 nodes and 841,038 elements in the intact model.

The interbody cage was modeled based on Nuvasive cage (Nuvasive, Inc., San Diego, California, USA). The standard cage was 15° lordosis, 10 mm high anteriorly, and 4 mm posteriorly. The cage was made of polyetheretherketone. The bilateral pedicle screw system was modeled based on the EXPEDIENT 5.5 System (DePuy Synthes Spine, Inc., Raynham, Massachusetts, USA). The diameter of pedicle screw was 5.5 mm. The material of the pedicle screws was titanium alloy (Ti6Al4V). The LP was modeled based...
on Nuvasive Decade plate, and the diameter of the LP bolts was 5.5 mm. The SPP was modeled based on Nuvasive Affix plate, and the size of the plate was 45 mm. Both of the plates were made of titanium alloy (Ti6Al4V). The material properties of components were shown in Table 1.23-31

To validate the intact FE model, the analysis study included 2 steps of simulation. First, the ROM of intact lumbar spine L1—L5 under pure moment was predicted. The ROM of the lumbar spine was compared with previous in vitro results.26,32 Then, the compression displacement and intervertebral disc pressure (IDP) of the motion segment L4—L5 under pure compression were calculated. The compression displacement and IDP of L4—L5 were compared with previous results.23-34

For simulation of the surgical models, the segment L2—L5 was chosen to predict the biomechanical changes of surgical level and adjacent levels. The interbody cage was inserted at the L3—L4 disc space laterally. The surgical conditions were as follows: intact (Intact), stand-alone cage (Cage), cage supplemented with LP, cage supplemented with ipsilateral pedicle screws (IPS), cage supplemented with SPP, cage supplemented with LP and SPP (combined fixation, CF), and cage supplemented with BPS. For the 2 models with SPP fixation (SPP and CF), the interspinous ligament and supraspinous ligament were resected. The FE models of interbody fusion constructs with various fixation options were shown in Figure 2. All the surgical FE models were constructed based on the validated intact model. The surface contact between the vertebrae and discs and the contact between the facet joints were consistent with that of the validated model. The interfaces of vertebrae and cages were assigned to tie constraints. The bottom of L5 was fixed in all directions. The compressive load of 280 N and the moment of 7.5 Nm were applied to the upper surface of L2 as in previous literature.35-36 The compressive load of 280 N corresponded to the partial weight of a human body, and the moment of 7.5 Nm simulated the motion modes occurred in different conditions such as flexion, extension, lateral bending, and axial rotation.

Considering the asymmetry of the LP fixation, this study simulated the biomechanical properties of surgical FE models in 6 motion modes: flexion, extension, bending-left, bending-right, rotation-left, and rotation-right. The ROM, cage stress, IDP, endplate stress, and FJS were analyzed and exported. The predicted results of LP, SPP, and CF were compared with that of BPS. The ROM data were normalized to the intact ROM data.4 Under the combined loading, the intact L2—L5 model was recalculated. In total, 42 simulation calculations for 7 models and 6 motion modes were performed. Simulation results were in accordance with the requirements of visualization, and mechanics data were expressed with Von Mises stress contours.

RESULTS

Model Validation
The FE model of the intact lumbar spine employed in this study was validated in our previous study.22 Under the pure moment, the

<table>
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<tr>
<th>Table 1. Material Properties Used in the Finite Element Models</th>
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<td><strong>Components</strong></td>
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<tr>
<td>Cortical bone</td>
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<tr>
<td>Cancellous bone</td>
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<td>Posterior bone</td>
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<td>Endplate</td>
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<td>Annulus fibrosus</td>
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<td>Nucleus pulposus</td>
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<tr>
<td>Anterior longitudinal ligament</td>
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<td>Posterior longitudinal ligament</td>
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<tr>
<td>Ligamentum flavum</td>
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<tr>
<td>Interspinous ligament</td>
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<td>Supraspinous ligament</td>
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<tr>
<td>Transverse ligament</td>
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<tr>
<td>Capsular ligament</td>
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<tr>
<td>Cage (PEEK)</td>
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<td>Pedicle screws (titanium alloy)</td>
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<td>Lateral plate (titanium alloy)</td>
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<td>Spinous process plate (titanium alloy)</td>
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PEEK, polyetheretherketone.
L1–L5 ROM was within the range of the previous FE and in vitro experimental studies. The load–deflection curves were comparable with the existing results of previous studies. The compression–displacement curves and compression–IDP curves also were compared with the previous FE and in vitro experimental studies.

**Range of Motion**
Under the combined loading of 280 N and 7.5 Nm, the ROM of surgical models is shown in Figure 3. After the interbody cage was inserted, the predicted ROM at surgical level L3–L4 decreased in all motion modes. ROM of IPS was slightly less than that of Cage. ROMs of LP, SPP, and CF were compared with that of BPS. LP reduced ROM in bending and rotation, whereas it increased ROM in flexion and extension. SPP reduced ROM in extension and rotation, whereas it did not substantially alter ROM in flexion and bending. CF reduced ROM in all motion modes. Compared among all the surgical models, ROM for CF was the minimum in all motion modes. Compared with BPS, ROMs for CF were reduced by 4.20% in flexion, 12.87% in extension, 34.98% in bending-left, 57.15% in bending-right, 64.27% in rotation-left, and 37.28% in rotation-right, respectively.

**Cage Stress and IDP**
The maximum stress in cage (cage stress) is displayed in Figure 4A. Cage stress of IPS was slightly less than that of Cage. Cage stresses of LP, SPP, and CF were compared with that of BPS. LP increased cage stress in all motion modes except for bending. SPP did not substantially alter cage stress in all motion modes. CF reduced cage stress in all motion modes. Compared among all the surgical models, cage stress for CF was the minimum in all motion modes except for flexion and rotation-right. Compared with BPS, cage stresses for CF were reduced by 10.97% in flexion, 17.06% in extension, 62.76% in bending-left, 11.91% in bending-right, 2.39% in rotation-left, and 13.46% in rotation-right, respectively. Figure 4B showed the contour plots of Von Mises stress in the cage for CF in different motion modes. The IDP at adjacent levels is displayed in Figure 5.
interbody fusion, the IDP at adjacent level L2–L3 increased in extension and bending-right, whereas it changed very little in flexion and rotation. Compared among the surgical models, The IDP at adjacent levels was not substantially changed with varied fixation options except for SPP in bending-right. The IDP for CF was similar to that for BPS.

**Endplate Stress**

Figure 6A depicts the maximum stress in endplates (endplate stress) at surgical level. After interbody fusion, the predicted endplate stresses at surgical level L3–L4 increased in all motion modes except for LP and CF in bending-left. Endplate stress of IPS was slightly less than that of Cage. Endplate stresses of LP, SPP, and CF were compared with that of BPS. LP increased endplate stress in flexion and extension, whereas it decreased that in bending-left. SPP did not substantially alter endplate stress in all motion modes. CF reduced endplate stress in all motion modes. Compared among all the surgical models, endplate stress for CF was the minimum in all motion modes except for flexion. In flexion, endplate stress for CF was slightly more than that for SPP. Compared with BPS, endplate stresses for CF were reduced by 12.11% in flexion, 20.90% in extension, 57.13% in bending-left, 9.97% in bending-right, 2.64% in rotation-left, and 14.00% in rotation-right, respectively. Figure 6B showed the contour plots of Von Mises stress in the L3 bottom endplate for CF in different motion modes.

**Facet Joint Stress**

In Figure 7, the FJS of intact and surgical models is displayed. After interbody fusion, FJS at surgical level L3–L4 decreased in all motion modes except for flexion. Compared among all the surgical models, FJS for various fixation options was not substantially changed in all motion modes except for flexion and bending-right. Compared with BPS, SPP and CF increased FJS in flexion and bending-right. However, FJS for all the fixation options was much smaller than that for the intact conditions in all motion modes except for flexion. Compared with the case of intact conditions, the average FJS for CF and BPS was reduced by 51% and 56%, respectively.

**DISCUSSION**

The predicted ROMs with various fixation options were normalized to the intact ROM data.4 In addition, the current study showed the cage stress, IDP, endplate stress, and FJS. As was displayed in Figure 3, the ROM decreased at surgical level after the cage was inserted at L3–L4 in all motion modes. Compared among all the fixation options, ROM for the CF was the minimum in all motion modes. As is displayed in Figures 4 and 5, the cage stress was sensitive to the various fixation options, whereas the IDP at adjacent levels was not substantially changed with various fixation options. Compared among all the fixation options, cage stress for CF was the minimum in all motion modes except for flexion and rotation-right. Figure 6 shows that the endplate stress increased at surgical level after the cage was inserted at L3–L4 in all motion modes. Compared among all the fixation options, endplate stress for CF was the minimum in all motion modes except for flexion. As is displayed in Figure 7, FJS decreased at surgical level after the cage was inserted at L3–L4 in all motion modes except for flexion. The average FJS for CF and BPS was reduced to about one half of that for the intact conditions. There was not a substantial difference in FJS between CF and BPS.

The ROM, cage stress, and endplate stress at L3–L4 were directly affected in all motion modes and changed with various fixation options (Figure 2). By comparing the biomechanics of lumbar fusion with different fixation options, it was shown that the CF displayed advantages at surgical level L3–L4, such as the minimum ROM in all motion modes, the minimum cage stress except for flexion and rotation-right, and the minimum endplate stress except for flexion. Compared with BPS, the combination of LP and SPP reduced ROM in all motion modes, which was not available when using LP or SPP alone. The CF reduced the ROM, which may provide better multiplanar stability than BPS.
particularly in low-demand patients. The CF reduced the cage stress and endplate stress, which may decrease the risk of subsidence of the cages into the endplate and the adjoining vertebral bone over time. It was indicated that in performing lateral lumbar interbody fusion, the combination of LP and SPP may offer an alternative to BPS in low-demand situations.

Biomechanics of lateral lumbar interbody fusion was sensitive to the different fixation options. The previous studies have shown that LP may increase stiffness in bending and rotation whereas it had little effect in flexion and extension. The predicted ROM in the current study was comparable with the previous in vitro experiments. In addition, the predicted results in the current study have shown that LP reduced cage stress and endplate stress in bending while changing little in other motion modes. From a biomechanical standpoint, LP had advantages in bending and rotation. Some studies have shown that SPP may reduce flexion–extension motion but is less effective in other motion modes.

Figure 4. Maximum stress in the cage with various fixation options in (A) 6 motion modes and (B) contour plots of Von Mises stress in the cage for CF. Cage, stand-alone cage; LP, cage with lateral plate; IPS, cage with ipsilateral pedicle screws; SPP, cage with spinous process plate; CF, cage with lateral plate and spinous process plate; BPS, cage with bilateral pedicle screws; L, left; R, right.
comparable with the previous in vitro experiments except for rotation. In addition, the predicted results in the current study have shown that SPP reduced cage stress and endplate stress in all motion modes. From a biomechanical standpoint, SPP had advantages in flexion, extension, and rotation. Because the LP and SPP showed biomechanical advantages in different motion modes, a combination of these plates may provide better biomechanical properties in all motion modes.

The basic idea of lumbar interbody fusion is to stabilize the lumbar spine by reducing the ROM at surgical level. The previous literature has shown that lumbar fusion may accelerate the degeneration of intervertebral discs at adjacent levels. In Figure 5, the IDP at adjacent level L2–L3 increased after interbody fusion in extension and bending-right, whereas at adjacent levels changed very little in flexion and rotation. In addition, the same load condition was considered in the present study, the IDP was not substantially increased at adjacent levels. However, to achieve the desired total ROM, patients after interbody fusion will increase the driving force naturally, which may further increase the risk of degeneration of intervertebral discs at adjacent levels.

In the current study, the 15° lordosis cage was chosen according to the foraminal height and disc space angle of the present lumbar model. In this study, the combined anterior—posterior fixation of LP and SPP was compared with BPS fixation. As was predicted in Figures 3, 4, and 6, the CF has advantages in ROM, cage stress, and endplate stress, which may provide better stability and lead to a smaller risk of endplate injury. In clinical practice, the CF can be placed in a single-position used for lateral procedure, avoiding an additional posterior procedure, which may be associated with shorter operative times, less invasiveness, and less blood loss.

There are some limitations in the present study, such as using a unique lumbar model, simplifying the material properties of some tissues, and ignoring the role of muscles. One limitation is the FEA standard technique of using a unique lumbar model. The geometric model of lumbar spine varies from person to person, such as the intervertebral disc space and the gaps between facet joints. However, only one model of lumbar spine was chosen in this study. Furthermore, the material properties were simplified, as linear elastic though the components of lumbar spine is

Figure 5. IDP at adjacent levels with various fixation options in flexion (A), in extension (B), in bending (C), and in rotation (D). D2, disc between L2 and L3; D4, disc between L4 and L5; BL, bending-left; BR, bending-right; RL, rotation-left; RR, rotation-right.
nonlinear in reality. However, many FEAs on lumbar spine have assumed that the components of spine were linear to improve the calculation efficiency. In addition, the muscles were not considered in the present study although the muscles play an important role in supporting the stability of lumbar spine. However, the tendency of predicted results with various fixation options would not be substantially changed depending on the individual geometric model and simplified material properties.

According to the predicted results using FEA, it was indicated that fixation options can affect the biomechanics of lumbar spine. For example, Figure 6 shows the maximum stress in the endplate at surgical level with various fixation options in 6 motion modes and contour plots of Von Mises stress in L3 bottom endplate for CF. Cage, stand-alone cage; LP, cage with lateral plate; IPS, cage with ipsilateral pedicle screws; SPP, cage with spinous process plate; CF, cage with lateral plate and spinous process plate; BPS, cage with bilateral pedicle screws; L, left; R, right.
interbody fusion noticeably. Compared among the surgical models with different fixation methods, a CF of LP and SPP showed advantages in biomechanics such as ROM, cage stress, and endplate stress. Compared with BPS fixation, the CF has advantages in biomechanics and may have advantages in lower-demand patients in clinical practice. An in vitro biomechanical testing or further clinical studies will be necessary to validate the observations of this FE study.

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