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Comparative Biomechanical Analysis of Anterior Lumbar Interbody Fusion and Bilateral Expandable Transforaminal Lumbar Interbody Fusion Cages: A Finite Element Analysis Study

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ABSTRACT

Background: Expandable transforaminal lumbar interbody fusion (TLIF) cages could offer an alternative to anterior lumbar interbody fusion (ALIF). Bilateral cage insertion enhances endplate coverage, potentially improving stability and fusion rates and maximizing segmental lordosis. This study aims to compare the biomechanical properties of bilateral expandable TLIF cages to ALIF cages using finite element modeling.

Methods: We used a validated 3-dimensional finite element model of the lumbar spine. ALIF and TLIF cages were created based on available product data. Our focus was on analyzing spinal motion in the sagittal plane, evaluating forces transmitted through the vertebrae, and comparing an ALIF model with various TLIF cage models.

Results: The largest TLIF cage model exhibited a 407.9% increase in flexion motion and a 42.1% decrease in extension motion compared with the ALIF cage. The second largest TLIF cages resulted in more flexion motion and less extension motion compared with ALIF, while smaller cages were inferior to ALIF. ALIF cages were associated with increased adjacent segment motion compared with TLIF cages, primarily in extension. Endplate stress analysis revealed higher stress in the ALIF cage model with a more uniform stress distribution.

Conclusion: ALIF cages excel in stabilizing L5 to S1 during flexion, while largest TLIF cages offer superior stability in extension. Large bilateral TLIF cages may provide biomechanical stability comparable to ALIF, especially in extension and could potentially reduce the risk of adjacent segment disease with lower adjacent segment motion.

Level of Evidence: 5.

Biomechanics

Keywords: transforaminal interbody fusion (TLIF), anterior lumbar interbody fusion (ALIF), finite element, bilateral TLIF, expandable cages, biomechanics

INTRODUCTION

The techniques for spinal fusion are intricate and necessitate a good understanding of various available methods to tailor patient care effectively.¹ Lumbar interbody fusion is a highly efficient approach for enhancing the biomechanical stability of the spine and increasing the fusion rates.^{1–3} A range of surgical techniques are available to accomplish interbody fusion, including anterior lumbar interbody fusion (ALIF), lateral lumbar interbody fusion, and transforaminal lumbar interbody fusion (TLIF).¹

ALIF is a reliable surgical option that provides direct access to the anterior column of the spine facilitating a comprehensive discectomy and allowing for the placement of a large interbody fusion device.² This allows for robust anterior column support and better distraction and decompression of neural elements.² These advantages lead to the correction of deformity, restoration of lordosis, and probable enhancement of fusion rates.² In contrast, TLIF offers an all-posterior approach that is more familiar to spine surgeons, allowing for the completion of spinal fusion in a single procedure without the need for an access surgeon.² However, when comparing TLIF to ALIF, the posterior approach typically results

in iatrogenic trauma to the spinal muscles, with a risk of nerve root injury, epidural scarring, and perineural scarring.^{2,4} On the other hand, ALIF does present certain drawbacks, including approach-related complications such as the risk of visceral and vascular injury and incisional hernia, and it generally requires the involvement of an access surgeon.^{4,5} There is a conflicting body of evidence regarding the rate of fusion of the TLIF and ALIF, with some studies suggesting an increase in fusion rates with ALIF and others suggesting that the fusion rates are similar.^{3,4,6-9} The utilization of expandable TLIF cages can mitigate some limitations associated with static cages,¹⁰ as they offer advantages such as improved height restoration and indirect decompression of neural elements.^{10,11} Bilateral cage insertion with complete resection of bilateral facet joints can be used as a method to achieve more effective lordosis correction and a larger cage footprint, potentially leading to an augmentation in fusion rates.¹¹

Finite element (FE) analysis is a powerful computational tool widely used in biomechanics to simulate complex mechanical and biological systems.¹² It involves breaking down anatomical structures into interconnected elements to study their behavior under different loads or conditions.¹² FE has been extensively applied to the musculoskeletal system, particularly in understanding spinal biomechanics and the impact of factors such as surgical procedures and implant designs.¹²⁻¹⁴ As technology has progressed, FE models have evolved to provide more flexibility and cost-effective simulations, surpassing the limitations of cadaver studies and enabling research not feasible in clinical settings.^{12,15} The FE models can undergo a validation process that typically involves comparing the model predictions to data obtained from human cadaver spine tests.¹² In our study, we employed a previously validated FE spine model that includes the 12th thoracic vertebra down to the first sacral vertebra.¹³ This model underwent validation using previously published experimental cadaveric data, making it suitable for application in clinical studies.¹³ In the context of ALIF vs bilateral TLIF expandable cages, there appears to be a current research gap in understanding the biomechanical properties of these surgical constructs. Bilateral expandable cages are capable of achieving superior lordotic correction compared with static cages, and their bilateral insertion provides a wider endplate coverage and a larger cage footprint compared with static cages. Our study aims to utilize a validated FE spine model to assess the biomechanical properties of ALIF vs expandable TLIF interbody fusion methods, with

the goal of gaining a better understanding of how these cages perform. This study focuses on investigating the stability across various spinal segments by comparing the stabilization achieved through ALIF cage placement at L5 to S1 with the use of different sizes of bilaterally inserted TLIF cages.

MATERIALS AND METHODS

We used a previously validated 3-dimensional FE model in this study. The model includes the vertebral bodies from the 12th thoracic spine down to the first sacral spine. The bony elements of the vertebral bodies were modeled to incorporate both cortical and trabecular components. Additionally, this model includes the intervertebral disc (with an annulus and nucleus pulposus) and the endplates of each vertebra. Soft tissue elements were also included, such as the anterior and posterior longitudinal ligaments, ligamentum flavum, interspinous ligaments, supraspinous ligaments, transverse ligaments, as well as capsular ligaments and synovial fluid located at the facet joints. The material properties for all these components were meticulously sourced from existing literature. The model underwent validation through a series of human cadaver experiments that replicated the magnitude of flexion and extension moments we used. The processes involved in the development and validation of this model have been comprehensively detailed in previous studies.

To simulate ALIF and TLIF cages, we used computer-aided design renders from the manufacturer's brochure to create the models. The computer-aided design geometry served as the basis for developing the finite-element model of the instrumentation. For ALIF cages, we created a model of the Globus Medical MONUMENT product, which measured 11 mm in height, 34 × 26 mm in width and length, and had 15° of lordosis. The total contact surface area of the cage with the cranial and caudal endplates of the vertebrae was 2194 mm². We used 4 screws, each measuring 5.5 mm in diameter and 30 mm in length, to stabilize the ALIF cage. Both the cage and screws were modeled as titanium material with an elastic modulus of 110 GPa and a Poisson's ratio of 0.3. We placed the ALIF cage with the stabilizing screws at the L5 to S1 level by performing a discectomy, which included the removal of the anterior longitudinal ligaments.

For TLIF cages, we utilized a model of the X-PAC expandable lumbar cage. The height of the TLIF cages used is 9 mm with a lordotic angle of 15°. We employed various widths and lengths based on the product brochure to create different cage sizes. Table 1 summarizes

Table 1. Dimensions of cages utilized in the study.

Cage	Height (mm)	Width (mm)	Length (mm)	Lordotic Angle (°)	Surface Area (mm ²)
TLIF cage 1	9	8	22	15	340
TLIF cage 2	9	10	25	15	484
TLIF cage 3	9	10	28	15	536
TLIF cage 4	9	12	28	15	652
TLIF cage 5	9	12	32	15	740
ALIF cage	11	34	26	15	2194

Abbreviations: ALIF, anterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.

the details of the cages used in our study. The process of cage insertion involved the removal of the spinous process at the L5 level (along with the connecting ligaments between L5 and S1, the supraspinous, and interspinous ligaments), a full laminectomy, and complete removal of the ligamentum flavum. We then performed a total L5 to S1 facetectomy bilaterally and a discectomy on each side of the model, after which each cage was tilted to a 45° angle and symmetrically positioned bilaterally. We used screws and rods to stabilize the L5 and S1 vertebrae posteriorly in both the ALIF and TLIF models. The posterior fixation screws measured 60 mm in length for the L5 vertebrae and 50 mm for the S1 vertebrae, with a diameter of 5 mm. The rods used also

measured 5 mm in diameter. Figure 1 provides details of the ALIF and TLIF models.

In our study, the intact T12-sacrum model, as well as the 6 lumbar spine interbody fusion models, was simulated under physiological pure-moment loading. The sacrum was fixed, and a pure moment loading of 10 Nm was applied at T12 in both flexion and extension. Table 2 summarizes the normal motion across the spine in our model. We applied this pure-moment loading methodology to our developed model. This was achieved by fixing the sacrum in all degrees of freedom and applying loading at the T12 vertebra. We subjected the model to pure-moment loading of up to 10 Nm at a quasistatic rate of 0.5 Nm/s.

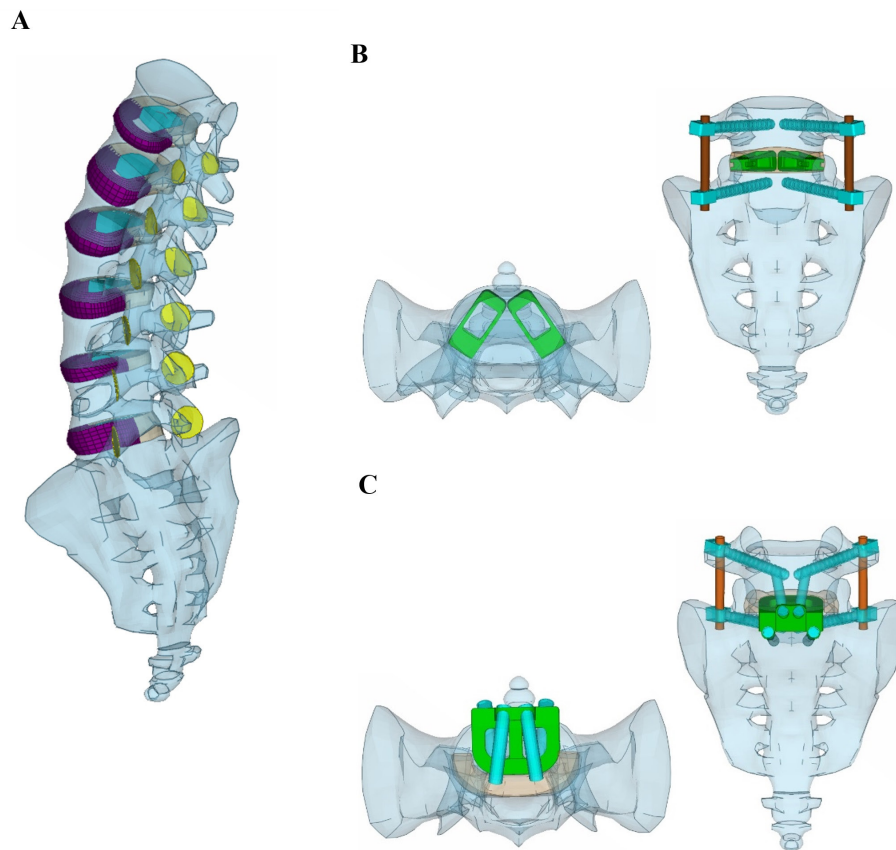


Figure 1. Three-dimensional representation of the finite element model. (A) Baseline intact model. (B) Axial (left) and posterior (right) views of the bilateral transforaminal lumbar interbody fusion model. (C) Anterior lumbar interbody fusion model with both lateral (left) and posterior (right) perspectives.

Table 2. Degrees of range of motion in the intact spine model and spine models with each cage inserted during flexion and extension.

Flexion	Intact	Cage 1 TLIF	Cage 2 TLIF	Cage 3 TLIF	Cage 4 TLIF	Cage 5 TLIF	ALIF Cage
T12-L1	4.36	4.41	4.41	4.40	4.41	4.41	4.39
L1-L2	4.48	4.58	4.58	4.56	4.58	4.59	4.53
L2-L3	3.33	3.39	3.39	3.36	3.39	3.40	3.35
L3-L4	5.21	5.50	5.47	5.40	5.47	5.50	5.33
L4-L5	4.01	3.65	3.89	3.95	3.98	4.22	4.04
L5-S1	8.89	1.85	1.64	1.52	1.28	0.93	0.18
Total	30.27	23.37	23.38	23.20	23.10	23.06	21.83
Extension	Intact	Cage 1 TLIF	Cage 2 TLIF	Cage 3 TLIF	Cage 4 TLIF	Cage 5 TLIF	ALIF Cage
T12-L1	5.43	5.47	5.46	5.46	5.46	5.47	5.52
L1-L2	3.57	3.62	3.65	3.65	3.58	3.58	3.81
L2-L3	3.08	3.19	3.19	3.19	3.19	3.19	3.17
L3-L4	3.64	3.71	3.70	3.70	3.69	3.69	3.68
L4-L5	1.43	1.63	1.69	1.86	1.94	2.17	2.51
L5-S1	7.54	0.71	0.68	0.53	0.25	0.19	0.33
Total	24.71	18.32	18.37	18.40	18.11	18.28	19.02

Abbreviations: ALIF, anterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.

We measured the range of motion of the spine within the sagittal plane for each segmental level and the complete models. We compared the range of motion in each model to determine the stability of the fixed level with each cage used. Additionally, we measured the pressure applied to bony structures and adjacent intervertebral discs to assess the impact of each cage on adjacent levels. Pressure values were reported in megapascals (MPa).

RESULTS

In this study, we compared the ALIF spine model with various models utilizing bilateral TLIF cages. The TLIF cages showed a smaller surface area in comparison to the ALIF cages. Bilateral insertion of the largest TLIF cage (cage 5) resulted in the coverage of 1480 mm² of the endplate, which is 32.5% less than that of the ALIF cage. The second-largest cage (cage 4) had a surface area of 1304 mm² when inserted bilaterally, reflecting a 40.6% reduction compared with the ALIF cage.

We conducted a comparative analysis of lumbar spine motion using both ALIF and bilateral TLIF cages to assess stability. In the ALIF model, motion at the L5 to S1 level was measured at 0.18° during flexion and 0.33° during extension. The model utilizing the largest TLIF cages (cage 5) exhibited a range of motion of 0.93° during flexion, representing a substantial increase of 407.9% compared with the ALIF cage. On the other hand, during extension, the motion was reduced to 0.19°, indicating a 42.1% decrease compared with the ALIF cages. The second largest cage (cage 4) resulted in 1.28° in flexion, leading to an increase in segmental motion when compared with the ALIF cage by 596.7%,

and 0.25° in extension, a 23.8% reduction in segmental motion compared with ALIF cages. Smaller TLIF cages consistently demonstrated inferior performance compared with the ALIF cages in both flexion and extension. Figure 2 shows a graphical comparison between the ALIF cage and the 2 largest TLIF cages in the range of motion across the different segments. Detailed findings of FE analysis of motion are presented in Table 2.

To assess the influence of stability on adjacent segments, we examined the motion at the L4 to L5 level. In the ALIF model, minimal changes were observed in flexion from baseline, with a 0.7% increase in flexion motion (from 4.01° to 4.04°), while the bilateral TLIF model (cage 5) exhibited a more pronounced 5.4% increase (Table 2). During extension, the ALIF cage led to a substantial 75% increase in motion across the L4 to L5 segment when compared with baseline (from 1.43° to 2.51°). On the other hand, the largest bilateral TLIF cages model showed a 51.5% increase (Table 2). Furthermore, the use of smaller TLIF cages was associated with diminished motion at the L4 to L5 segments.

Examining endplate stress, the ALIF cage in general exhibited higher stress levels compared with the bilateral TLIF cages. During flexion, the ALIF cage generated a pressure of 14.21 MPa on the L5 endplate, in contrast to 6.59 MPa in cage 5, representing a 115.7% increase in pressure. In extension, the ALIF cage produced a pressure of 13.56 MPa on the L5 endplate, while the cage 5 model resulted in 4.62 MPa (177.29% increase in stress). Shifting the focus to S1, during flexion, the ALIF cage resulted in 11.83 MPa of stress, compared with 6.66 MPa in the largest TLIF cage model, indicating a 77.65% increase in stress. Interestingly, in extension, the TLIF cage 5 model exhibited slightly higher

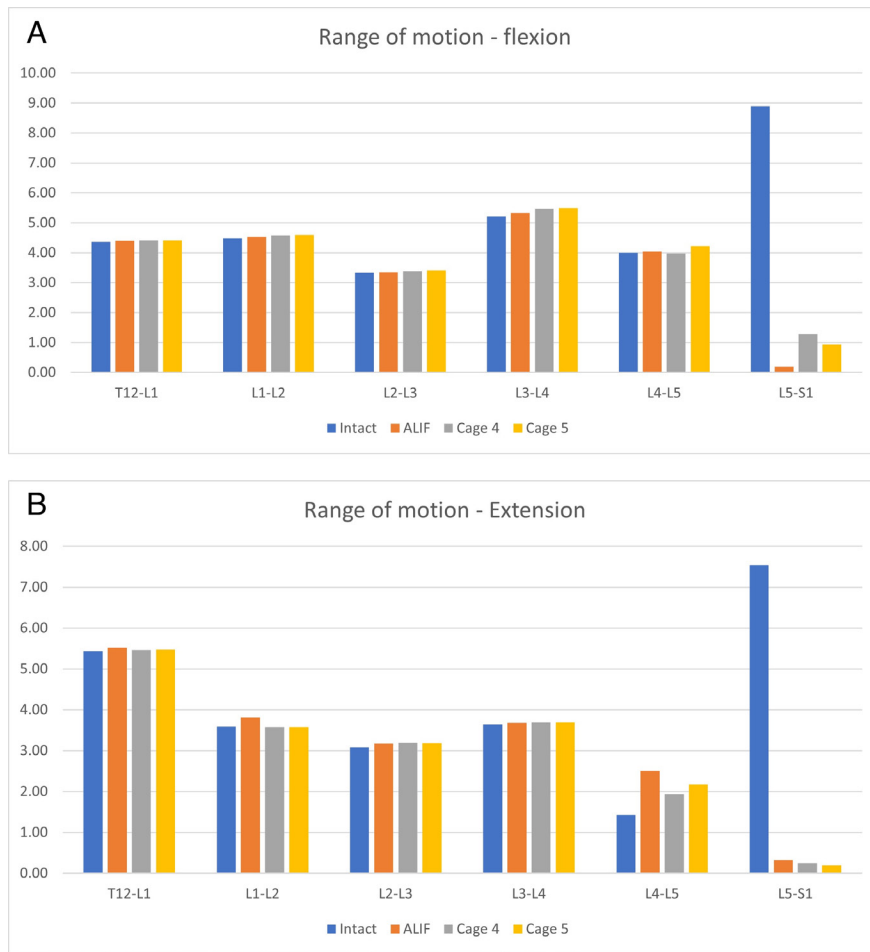


Figure 2. Comparative analysis of motion at each vertebral segment in the anterior lumbar interbody fusion (ALIF) model and the 2 largest transforaminal lumbar interbody fusion (TLIF) cage models during flexion (A) and extension (B).

stress on the S1 endplate when compared with the ALIF cage (11.9 vs 11.66 MPa, a marginal 1.99% increase). Detailed information on the distribution of stress on the endplates is presented in Table 3.

DISCUSSION

Our analysis revealed that the ALIF model provided significantly greater stabilization in flexion compared with the TLIF models; in extension, the TLIF model demonstrated increased stability. Previous cadaveric

studies have also indicated statistically significant differences in flexion and extension when comparing TLIF and ALIF procedures.¹⁶⁻¹⁸ The enhanced flexion stability with ALIF cages is likely attributed to the additional anterior column support that they offer,¹⁹ in contrast to TLIF cages that leave a small anterior gap, resulting in increased motion during flexion. On the other hand, TLIF cages offer greater posterior support, contributing to improved segment stability. Kaipour et al. demonstrated in their biomechanical study that ALIF

Table 3. Endplate stress at L5 to S1 level measured in MPa.

Flexion	Cage 1 TLIF	Cage 2 TLIF	Cage 3 TLIF	Cage 4 TLIF	Cage 5 TLIF	ALIF Cage
L5	7.52	7.08	6.21	5.90	6.59	14.22
S1	7.44	6.46	6.45	6.19	6.66	11.83
Extension	Cage 1 TLIF	Cage 2 TLIF	Cage 3 TLIF	Cage 4 TLIF	Cage 5 TLIF	ALIF cage
L5	2.35	3.51	4.57	4.62	4.89	13.56
S1	4.65	8.05	8.50	9.32	11.90	11.66

Abbreviations: ALIF, anterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.

was superior to TLIF cages in both flexion and extension, resulting in a superior reduction in motion, which is different from our reported results.¹⁸ In their TLIF technique, they utilized a banana-shaped cage measuring 30 mm in length and 10 mm in anterior-posterior width.¹⁸ In our study, the largest cage dimensions used were 32 × 12 mm, and they were inserted bilaterally, contributing to the increased stability observed in our results.

Furthermore, our study observed that the overall movement in adjacent segments was more affected by ALIF cages than TLIF cages. This observation suggests an association between the increased stress on adjacent segments and the stabilization of the L5 to S1 level. Clinical studies have reported an elevated risk of adjacent segment disease when comparing ALIF and static TLIF procedures.²⁰ This could be attributed to the heightened stress experienced by adjacent segments due to fusion. Future investigations could explore a comparison of adjacent segment disease between static and expandable cages, considering the superior stability demonstrated by expandable cages in our study. Additionally, the ALIF cage demonstrated a higher increase in endplate stress when compared with TLIF cages. This increase in stress is spread over the broader contact area of ALIF cages, resulting in a more uniform stress distribution. Faizan et al. have shown similar results to our study concerning stress distribution in cages with a larger footprint.²¹ This is an added advantage that may potentially decrease the risk of cage subsidence and contribute to increasing the fusion rate when compared with TLIF cages. Multiple studies have shown higher subsidence rates in TLIF cages compared with ALIF cages.^{9,22,23} A major drawback in these studies is that the TLIF cases were done unilaterally, leading to focal stress due to the smaller footprint. It would be interesting for future clinical studies to investigate the rate of subsidence related to the bilateral insertion of large TLIF cages.

While this study provides a novel insight into the biomechanics of ALIF and bilateral expandable TLIF cages, it is essential to acknowledge the inherent limitations associated with FE studies. Our model is based on data obtained from cadaveric studies, which may not fully represent the patient population undergoing surgical interventions. Additionally, the validated model does not encompass the pelvic region, which presents challenges in simulating fusion that stabilizes the spine to the pelvic region. Addressing these limitations should be a focal point for future research endeavors.

In conclusion, our study demonstrates that ALIF cages provide enhanced stabilization at the L5 to S1 level compared with bilaterally inserted TLIF cages during flexion.

On the other hand, in extension, large bilateral TLIF cages offer greater stability at the same level. Our findings indicate that the insertion of bilateral large expandable cages can result in biomechanically comparable stability to an ALIF cage. We found that adjacent segment motion was less with bilaterally inserted TLIF cages compared with ALIF. This could potentially be an option to decrease the chance of developing adjacent segment disease.

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