Biomechanical analysis of an expandable lateral cage and a static transforaminal lumbar interbody fusion cage with posterior instrumentation in an in vitro spondylolisthesis model

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OBJECTIVE Insufficient biomechanical data exist from comparisons of the stability of expandable lateral cages with that of static transforaminal lumbar interbody fusion (TLIF) cages. The purpose of this biomechanical study was to compare the relative rigidity of L4–5 expandable lateral interbody constructs with or without additive pedicle screw fixation with that of L4–5 static TLIF cages in a novel cadaveric spondylolisthesis model.

METHODS Eight human cadaver spines were used in this study. A spondylolisthesis model was created at the L4–5 level by creating 2 injuries. First, in each cadaver, a nucleotomy from 2 channels through the anterior side was created. Second, the cartilage of the facet joint was burred down to create a gap of 4 mm. Light-emitting-diode tracking markers were placed at L-3, L-4, L-5, and S-1. Specimens were tested in the following scenarios: intact model, bilateral pedicle screws, expandable lateral 18-mm-wide cage (alone, with unilateral pedicle screws [UPSs], and with bilateral pedicle screws [BPSs]), expandable lateral 22-mm-wide cage (alone, with UPSs, and with BPSs), and TLIF (alone, with UPSs, and with BPSs). Four of the spines were tested with the expandable lateral cages (18-mm cage followed by the 22-mm cage), and 4 of the spines were tested with the TLIF construct. All these constructs were tested in flexion-extension, axial rotation, and lateral bending.

RESULTS The TLIF-alone construct was significantly less stable than the 18- and 22-mm-wide lateral lumbar interbody fusion (LLIF) constructs and the TLIF constructs with either UPSs or BPSs. The LLIF constructs alone were significantly less stable than the TLIF construct with BPSs. However, there was no significant difference between the 18-mm LLIF construct with UPSs and the TLIF construct with BPSs in any of the loading modes.

CONCLUSIONS Expandable lateral cages with UPSs provide stability equivalent to that of a TLIF construct with BPSs in a degenerative spondylolisthesis model.

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KEY WORDS lateral lumbar interbody fusion; transforaminal lumbar interbody fusion; pedicle screw; biomechanical

DEGENERATIVE lumbar spondylolisthesis is one of many causes of spinal stenosis. Conservative nonsurgical management is the mainstay of treatment.²⁷ However, when nonoperative treatment fails, there are a number of different surgical options. Lateral lumbar interbody fusion (LLIF) performed using a transposas approach is a minimally invasive technique that can be used

to treat patients with degenerative lumbar spondylolisthesis and resulting neuroforaminal stenosis.^{1,3,20,23,30}

The morbidity rate for minimally invasive LLIF for degenerative scoliosis has been reported to be lower than that for traditional posterior open procedures.^{2,8,14} Studies have shown reduced hospital stay, less blood loss, and decreased narcotic use with LLIF.^{1,2} Fusion rates for both

ABBREVIATIONS BPS = bilateral pedicle screw; CLn = n-mm Caliber-L cage; HSD = Tukey's honest significant difference; LLIF = lateral lumbar interbody fusion; LLIFn = n-mm LLIF cage; ROM = range of motion; TLIF = transforaminal lumbar interbody fusion; UPS = unilateral pedicle screw.

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procedures are similar and may be, in some cases, superior with LLIF. Although a lateral approach for degenerative spondylolisthesis may be more technically difficult, it may have an advantage with a decreased morbidity rate for this pathology.

Lateral interbody cages are all indicated for use with supplemental pedicle fixation. Stand-alone lateral interbody constructs can be used, but there have been reports of subsidence with 18-mm and, to a lesser degree, 22-mm cages.¹⁶ It is advantageous to use an expandable cage because it provides increasing stability when compared with that of a static cage.¹² A stand-alone lateral procedure is advantageous because there is no need for separate surgical sites or for repositioning the patient, which increase operative times and cost expenditures. However, failure of a stand-alone lateral construct can lead to continued pain and disability and to reoperation.^{17,18} Posterior pedicle fixation to decrease this risk and further increase the stability of a construct can be added to enhance the strength of the construct and optimize patient treatment while reducing subsequent morbidity. Previous studies have examined both unilateral pedicle screw (UPS) and bilateral pedicle screw (BPS) fixation and found that their effectiveness was similar.^{9,29}

The purpose of this study was to examine the relative stability of the expandable lateral construct compared with that of a static transforaminal lumbar interbody fusion (TLIF) cage. To our knowledge, no biomechanical study has been performed to compare lateral expandable cages with or without posterior pedicle screw augmentation with static TLIF cages with or without posterior pedicle screw augmentation.

Methods

Specimen Preparation and Characteristics

Lumbosacral motion segments (L3–S1) were dissected from 8 fresh-frozen cadaveric specimens. The average age of the cadavers was 59 years (range 46–70 years). There were 5 male and 3 female cadavers. Dual-energy x-ray absorptiometry (DEXA) scans were not obtained; however, no implant or screw loosening was subsequently noted during the study. Anterior-posterior and lateral radiographs, as well as visual inspection, were used to confirm that the specimens were free of fractures, deformities, and any metastatic diseases. Before actual testing, the spines were dissected by carefully denuding the paravertebral musculature while avoiding disruption of spinal ligaments, joints, and intervertebral discs. The specimens were kept frozen and then thawed to room temperature before use. Specimens were potted, incorporating half of the L-3 vertebral body at the superior end and half of the S-1 vertebral body at the inferior end, with the L3–4 level positioned horizontally.

Test Apparatus

All the spines were tested sequentially on a custom-built 6-degrees-of-freedom spine simulator. The spine-simulator design, which is based on frictionless air-bearing rails, enables unconstrained motion of the spine in response to an applied load. The S-1 vertebra of each spine was fixed

to the load frame of the spine simulator, and a pure moment was applied to the L-3 vertebra through servomotors. Three infrared light-emitting diodes, mounted noncollinearly on a Plexiglas plate, were rigidly attached to the anterior aspect of each vertebral body. The 3D range of motion (ROM) of each segment was tracked by an Optotrak Certus (NDI, Inc.) motion-analysis system. L4–5 ROM was recorded in the form of Euler angles (degrees) from all 3 Cartesian axes for flexion-extension, lateral bending, and axial rotation, respectively.

Test Protocol

Each construct was tested under 3 loading conditions, flexion-extension, lateral bending, and axial rotation, by using a load-control protocol of $\pm 8 \text{ N}\cdot\text{m}$ applied at a rate of $1^\circ/\text{second}$. Eight human cadaver spines (L3–S1) were tested on a 6-degrees-of-freedom spine simulator in flexion-extension, lateral bending, and axial rotation with a load of $\pm 8 \text{ N}\cdot\text{m}$ to measure ROM.

Degenerative Spondylolisthesis Model

Degenerative spondylolisthesis was simulated by performing a nucleotomy through 2 anterior channels (Fig. 1) and by creating a 4-mm gap in the facet joint at L4–5 (Fig. 2). During the nucleotomy, a significant amount of disc was resected. Furthermore, burring of the facets helped to create further destabilization, resulting in a biomechanical model similar to that proposed by Crawford et al.⁷

Instrumentation of Cadaveric Specimens

A number of instrumentation methods were investigated at the L4–5 level. Four of the 8 spines were tested with the lateral expandable cage constructs. For the lateral cages, the 18-mm construct (LLIF₁₈, Caliber-L [CL], Globus Medical) was inserted. This stand-alone cage underwent the biomechanical testing described above. UPS and BPS fixation were both tested separately with the lateral 18-mm cage. After testing of these 3 constructs, all hard-

FIG. 1. Nucleotomy and disc resection performed through 2 anterior channels to simulate degenerative spondylolisthesis. Figure is available in color online only.

FIG. 2. Four-millimeter gap created in the facet joint at L4–5 to simulate degenerative spondylolisthesis. Figure is available in color online only.

ware was removed, and the 22-mm cage (LLIF₂₂, CL) was inserted after the lateral discectomy was widened slightly to accommodate the larger construct. This construct was again tested alone and with UPS and BPS fixation.

The other 4 spines were tested separately with the static interbody TLIF cage constructs (Sustain O, Globus Medical). A unilateral facetectomy was performed to insert the cage. Biomechanical testing was performed with the stand-alone cage, UPSs, and BPSs. For each spine, we radiographically measured the intact disc height and matched the implant heights to that of the intact condition. All of the instrumentations were performed by the senior author (J.R.O.) and were noted to be equally snug. The sizing of the TLIF cage ranged from 8 to 10 mm in width, 9 to 12 mm in height, and 26 to 30 mm in length based on specific cadaveric anatomy.

The test sequence was as follows: 1) intact, 2) BPSs, 3) spondylolisthesis model, 4) LLIF₁₈ alone, 5) LLIF₁₈ plus UPSs, 6) LLIF₁₈ plus BPSs, 7) LLIF₂₂ alone, 8) LLIF₂₂ plus UPSs, 9) LLIF₂₂ plus BPSs, 10) TLIF cage alone, 11) TLIF cage plus UPSs, and 12) TLIF cage plus BPSs.

The pedicle screws used were 6.5 mm in diameter and 45 mm in length and were the same for both the LLIF and TLIF constructs. In half (4 of 8) of the spines, the LLIF constructs were tested after creating the injury, followed by the TLIF constructs, and for the remaining 4 spines, the TLIF constructs were tested after creating the injury, followed by the LLIF constructs.

Randomization was performed between the lateral interbody cages and the TLIF construct to test after the spondylolisthesis model construct. Two preload cycles were applied before each loading condition to minimize the viscoelastic response of the spine. Data were collected during the third loading cycle. During testing, the models were moistened with 0.9% sodium chloride irrigation.

In all cases, to alleviate the homogeneity of variance, log transforms in the form of $\log_{10}$ (raw data + 1) were applied to the raw data, and then repeated-measures ANOVA was performed for significance ($p < 0.05$). After completing the ANOVA, Tukey's honest significant difference

(HSD) post hoc test was used to determine which groups in the sample differed from each other. Data achieved statistical significance if the difference in the means of the 2 study groups was greater than or equal to the HSD value generated by the post hoc test.

Results

The ROM for each construct is shown in Fig. 3, and the ROMs for all 12 models in flexion-extension, lateral bending, and axial rotation are shown as well (Fig. 3).

Data and their significance are listed in Tables 1–3.

Flexion-Extension

When tested, all the constructs resulted in significantly decreased ROM compared with that of the intact and spondylolisthesis models except for the stand-alone TLIF cage. There was no significant difference found between the LLIF₁₈+BPSs, LLIF₂₂, and TLIF+BPSs groups. There was no significant difference between the LLIF₁₈ and stand-alone LLIF₂₂. The stand-alone TLIF construct was significantly less stable than all the LLIF₁₈ constructs, and all LLIF₂₂s, TLIF+UPSs, and TLIF+BPSs. Both the LLIF₁₈ and the LLIF₂₂ alone were less stable than the TLIF+BPS construct.

Lateral Bending

All of the test constructs significantly reduced ROM over that with the intact model except for TLIF+UPSs. All of the test constructs significantly reduced ROM over that of the spondylolisthesis model injury except for the TLIF construct alone. There was no significant difference between BPSs and LLIF₁₈, LLIF₂₂, and TLIF+BPSs. There was no significant difference between stand-alone LLIF₁₈ and LLIF₂₂. The TLIF cage alone was significantly less stable than all CL₁₈ and CL₂₂ constructs and less stable than TLIF+UPSs and TLIF+BPSs. There was not a significant difference between the LLIF₁₈, LLIF₂₂, and TLIF+BPSs.

Axial Rotation

All of the test constructs significantly reduced ROM over that of the intact model except for CL₁₈+UPSs, CL₂₂+UPSs, and TLIF+BPSs. All of the test constructs significantly reduced ROM over that of the spondylolisthesis model except for the stand-alone LLIF₁₈ and stand-alone TLIF cage. There was no significant difference between BPSs and LLIF₁₈+BPSs, LLIF₂₂+BPSs, or TLIF+BPSs. There was no significant difference between the stand-alone LLIF₁₈ and LLIF₂₂. The stand-alone TLIF was significantly less stable than all the LLIF₁₈s, all LLIF₂₂s, and the TLIF+UPSs and TLIF+BPSs. The stand-alone LLIF₁₈ and LLIF₂₂ were significantly less stable than TLIF+BPSs.

Discussion

In this experimental model, we recreated a Grade I spondylolisthesis with 2 injuries: a 4-mm facet joint burring and a nucleotomy. Restabilization of the experimentally created listhesis was performed with 1) posterior pedicle instrumentation, 2) LLIF with and without instru-

FIG. 3. Range of motion for each construct. Each construct was tested in flexion-extension, lateral bending, and axial rotation. Spondy = spondylolisthesis model; LLIF 18mm = 18-mm LLIF cage; LLIF 22mm = 22-mm LLIF cage. Figure is available in color online only.

mentation, and 3) TLIF with and without instrumentation. Comparisons were made between these modes of treatment of a Meyerding Grade I spondylolisthesis.

Lateral interbody fusion has gained acceptance in many medical centers for the treatment of spondylolisthesis, stenosis, scoliosis, tumors, and trauma.^{3,8,20} Generally, decompression of the neural elements is achieved by realignment of the spine and distraction of the vertebral bodies to restore neuroforaminal height and open the central zone. Reports have shown up to a 54% increase in

the anterior-to-posterior plane and a 48% increase in the medial-lateral plane after LLIF.¹¹ Kepler et al.¹⁵ showed an average foraminal increase of 35% after lateral cage placement.

Good clinical outcome after LLIF partially depends on the avoidance of subsidence. A number of studies have examined the relative stability of 18-mm and 22-mm cages for LLIF,¹⁶ and although stand-alone LLIF is off-label use, many surgeons do perform LLIF without supplemental fixation and encounter good results. Supplemental fixation

TABLE 1. Tukey's HSD post hoc analysis for all the study groups in flexion-extension*

Flex-Ex	Intact	Spondy	BPSs	LLIF ₁₈	LLIF ₁₈ +UPSs	LLIF ₁₈ +BPSs	LLIF ₂₂	LLIF ₂₂ +UPSs	LLIF ₂₂ +BPSs	TLIF	TLIF+UPSs
Spondy	0.15†										
BPSs	0.42†	0.57†									
LLIF ₁₈	0.35†	0.50†	0.07								
LLIF ₁₈ +UPSs	0.59†	0.74†	0.17†	0.24†							
LLIF ₁₈ +BPSs	0.75†	0.90†	0.33†	0.40†	0.16†						
LLIF ₂₂	0.44†	0.59†	0.02	0.09	0.15†	0.30†					
LLIF ₂₂ +UPSs	0.63†	0.78†	0.21†	0.28†	0.04	0.11	0.19†				
LLIF ₂₂ +BPSs	0.76†	0.91†	0.34†	0.41†	0.18†	0.02	0.13†	0.13†			
TLIF	0.10	0.05	0.52†	0.45†	0.69†	0.85†	0.86†	0.73†	0.86†		
TLIF+UPSs	0.16†	0.31†	0.26†	0.19†	0.43†	0.59†	0.26†	0.48†	0.61†	0.26†	
TLIF+BPSs	0.51†	0.66†	0.09	0.16†	0.08	0.24†	0.35†	0.12	0.26†	0.35†	0.35†

Flex-Ex = flexion-extension; Spondy = spondylolisthesis model.

* The HSD in flexion-extension was 0.13. If the difference in the mean value of the 2 constructs (row and column) is greater than or equal to the HSD value, then it is statistically significant.

† Significant at a $p < 0.05$, as the difference in the means of 2 study groups is greater than or equal to the HSD value.

TABLE 2. Tukey's HSD post hoc analysis for all the study groups in lateral bending*

LB	Intact	Spondy	BPSs	LLIF ₁₈	LLIF ₁₈ +UPSs	LLIF ₁₈ +BPSs	LLIF ₂₂	LLIF ₂₂ +UPSs	LLIF ₂₂ +BPSs	TLIF	TLIF +UPSs
Spondy	0.12†										
BPSs	0.53†	0.65†									
LLIF ₁₈	0.46†	0.58†	0.07								
LLIF ₁₈ +UPSs	0.57†	0.69†	0.04	0.11							
LLIF ₁₈ +BPSs	0.67†	0.79†	0.14†	0.21†	0.10						
LLIF ₂₂	0.43†	0.55†	0.10	0.03	0.14†	0.24†					
LLIF ₂₂ +UPSs	0.54†	0.66†	0.01	0.08	0.03	0.13†	0.11				
LLIF ₂₂ +BPSs	0.65†	0.76†	0.11	0.18†	0.08	0.02	0.21†	0.10			
TLIF	0.18†	0.07	0.72†	0.64†	0.75†	0.85†	0.61†	0.72†	0.83†		
TLIF+UPSs	0.03	0.15†	0.50†	0.43†	0.54†	0.64†	0.40†	0.51†	0.61†	0.21†	
TLIF+BPSs	0.49†	0.61†	0.04	0.03	0.08	0.18†	0.06	0.05	0.15†	0.67†	0.46†

LB = lateral bending.

* The HSD in lateral bending was 0.12. If the difference in the mean value of the 2 constructs (row and column) is greater than or equal to the HSD value, then it is statistically significant.

† Significant at a $p < 0.05$, as the difference in the means of 2 study groups is greater than or equal to the HSD value.

is an important consideration for preventing fracture and subsidence.²⁵

Supplemental fixation may include open or percutaneous pedicle fixation. Pedicle screws offer 3-column fixation. TLIF has been performed with success for degenerative spondylolisthesis.²¹ Both BPS and UPS fixation methods have been used with TLIF cages for degenerative conditions.²⁴ There are a number of studies that demonstrated the efficacy of both methods, and some studies showed biomechanical inferiority of TLIF cages with UPSs to TLIF cages with BPSs.^{22,24} More recent studies and a meta-analysis showed no difference in functional outcomes between TLIF cages with BPSs and TLIF cages with UPSs.^{9,26,29} The results of our study, similar to previous biomechanical studies, show that a TLIF cage without

posterior supplemental fixation is significantly less stable than a TLIF cage with UPSs or BPSs.^{13,19} Our study reinforces the idea that stand-alone TLIF cages may not provide adequate segmental stability in degenerative spondylolisthesis.

Regardless of unilateral or bilateral fixation, all TLIF surgeries are done with a facetectomy. LLIF does not require a facetectomy or laminectomy and therefore may provide more inherent stability. Previous biomechanical studies have shown that lateral interbody implants may provide the greatest reduction in ROM and that with additive bilateral pedicle fixation, the reduction in ROM is similar to that with other interbody techniques.^{4,6} In this setting, we found that LLIF cages with UPSs afforded the same stability as a TLIF construct with bilateral screws.

TABLE 3. Tukey's HSD post hoc analysis for all the study groups in axial rotation*

AR	Intact	Spondy	BPSs	LLIF ₁₈	LLIF ₁₈ +UPSs	LLIF ₁₈ +BPSs	LLIF ₂₂	LLIF ₂₂ +UPSs	LLIF ₂₂ +BPSs	TLIF	TLIF +UPSs
Spondy	0.41†										
BPSs	0.17†	0.58†									
LLIF ₁₈	0.27†	0.14	0.44†								
LLIF ₁₈ +UPSs	0.01	0.40†	0.18†	0.26†							
LLIF ₁₈ +BPSs	0.22†	0.63†	0.05	0.49†	0.23†						
LLIF ₂₂	0.26†	0.16†	0.42†	0.02	0.25†	0.47†					
LLIF ₂₂ +UPSs	0.02	0.39†	0.19†	0.25†	0.01	0.24†	0.23†				
LLIF ₂₂ +BPSs	0.17†	0.58†	0.01	0.44†	0.18†	0.04	0.43†	0.19†			
TLIF	0.48†	0.07	0.65†	0.21†	0.47†	0.70†	0.23†	0.46†	0.66†		
TLIF+UPSs	0.24†	0.17†	0.40†	0.04	0.23†	0.45†	0.02	0.22†	0.41†	0.25†	
TLIF+BPSs	0.13	0.54†	0.04	0.40†	0.14	0.09	0.38†	0.15†	0.05	0.61†	0.36†

AR = axial rotation.

* The HSD in axial rotation was 0.15. If the difference in the mean value of the 2 constructs (row and column) is greater than or equal to the HSD value, then it is statistically significant.

† Significant at a $p < 0.05$, as the difference in the means of 2 study groups is greater than or equal to the HSD value.

The clinical significance of this finding pertains to ease of operation. Placing a UPS on the side that is up when the patient is in the lateral position is generally more easily done than placing BPSs while in the lateral position. By performing an LLIF with UPS fixation, the surgeon can avoid flipping the patient prone, which reduces operating time and morbidity.

It is important to recognize the limitations of this study, which are similar to those of other biomechanical studies. First, the sample size was small, and there may have been variable bone mineral densities and preexisting intervertebral motion differences. Although the sample size was small, it is still in accordance with the minimum number of specimens required to delineate the differences between various instrumented constructs.²⁸ Creating a spondylolisthesis model by performing a nucleotomy and burring the facets may have not accurately recreated true disease pathologies; however, it has been done in previous biomechanical studies.⁷ Second, the testing method enabled us to study immediate stability only and did not take into account additional biological changes that occur in vivo. Osteoporosis may limit the applicability of these results, because a fracture may occur in the vertebral body after LLIF.¹⁰ There have also been reports indicating that fracture may occur even without osteoporosis.⁵ Furthermore, we did not perform pretesting dual-energy X-ray absorptiometry scans on the cadavers; however, this model was created to determine biomechanical stability, not to perform catastrophic or fatigue testing. In addition, rotational control is generally better with BPS fixation and has yet to be studied in clinical long-term studies. Finally, the fatigue behavior of UPS fixation was not characterized in this study and would need to be characterized in additional biomechanical studies. Some patients may not be able to undergo a lateral procedure at L4–5 secondary to anatomical issues; however, this level was chosen for the study because it is the most frequently affected level in degenerative spondylolisthesis. In addition, this study was performed in a cadaveric model, and application in the clinical setting may not be valid.

Another potential limitation is that the constructs tested may not be equivalent, because an expandable cage was used in the LLIF construct and a static cage was used in the TLIF construct. A recent biomechanical study in which expandable and static lateral interbody cages were compared found that both constructs provide similar immediate stability to a single spine segment. The study concluded that although an expandable cage may be an attractive option for less tissue disruption during implantation, it resulted in higher endplate collapse as a result of overdistraction of the disc space after insertion. The most stable construct was the static lateral interbody cage with BPSs.¹²

Conclusions

In a degenerative spondylolisthesis model, expandable lateral cages with UPSs provide stability equivalent to that of a TLIF construct with BPSs.

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Disclosure

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Author Contributions

Conception and design: O'Brien, Mantell, Cyriac. Acquisition of data: O'Brien, Mantell, Gudipally. Analysis and interpretation of data: O'Brien, Mantell, Cyriac. Drafting the article: O'Brien, Mantell, Cyriac. Critically revising the article: O'Brien, Mantell, Cyriac, Haines. Reviewed submitted version of manuscript: O'Brien, Mantell, Cyriac, Haines. Statistical analysis: Gudipally. Study supervision: O'Brien.

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