


Biomechanical Comparison of Unilateral and Bilateral Pedicle Screw Fixation after Multilevel Lumbar Lateral Interbody Fusion

Global Spine Journal
2022, Vol. 0(0) 1–8
© The Author(s) 2022
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/21925682221149392
journals.sagepub.com/home/gsj


James M. Mok, MD, MBA¹, Craig Forsthoefel, MD², Roberto Leonardo Diaz, PhD² ,
Ye Lin, MD², and Farid Amirouche, PhD^{1,2} 

Abstract

Study Design: Human Cadaveric Biomechanical Study

Objectives: Lumbar Lateral Interbody Fusion (LLIF) utilizing a wide cage has been reported as having favorable biomechanical characteristics. We examine the biomechanical stability of unilateral pedicle screw and rod fixation after multilevel LLIF utilizing 26 mm wide cages compared to bilateral fixation.

Methods: Eight human cadaveric specimens of L1-L5 were included. Specimens were attached to a universal testing machine (MTS 30/G). Three-dimensional specimen range of motion (ROM) was recorded using an optical motion-tracking device. Specimens were tested in 3 conditions: 1) intact, 2) L1-L5 LLIF (4 levels) with unilateral rod, 3) L1-L5 LLIF with bilateral rods.

Results: From the intact condition, LLIF with unilateral rod decreased flexion-extension by 77%, lateral bending by 53%, and axial rotation by 26%. In LLIF with bilateral rods, flexion-extension decreased by 83%, lateral bending by 64%, and axial rotation by 34%. Comparing unilateral and bilateral fixation, LLIF with bilateral rods reduced ROM by a further 23% in flexion-extension, 25% in lateral bending, and 11% in axial rotation. The difference was statistically significant in flexion-extension and lateral bending ($P < .005$).

Conclusions: Considerable decreases in ROM were observed after multilevel (4-level) LLIF utilizing 26 mm cages supplemented with both unilateral and bilateral pedicle screws and rods. The addition of bilateral fixation provides a 10-25% additional decrease in ROM. These results can inform surgeons of the incremental biomechanical benefit when considering unilateral or bilateral posterior fixation after multilevel LLIF.

Keywords

lateral lumbar interbody fusion, XLIF, DLIF, OLIF, LLIF, posterior segmental instrumentation, pedicle screw, unilateral, bilateral, biomechanics, cadaveric, multilevel, multiple level

Introduction

Lateral lumbar interbody fusion (LLIF) is a minimally invasive technique of lumbar arthrodesis with reported fusion rates as high as 97.9%.¹ The disc space can be accessed via a retroperitoneal trans-psoas or anterior-to-psoas approach.¹⁻⁴ Both are usually performed with the patient in the lateral decubitus position to permit the approach, disc space preparation, and implantation of the interbody cage. Supplemental internal fixation is often combined with the interbody device

¹ NorthShore University HealthSystem, Skokie, IL, USA

² Department of Orthopaedics, University of Illinois at Chicago, Chicago, IL, USA

Corresponding Author:

Farid Amirouche, Department of Orthopaedics, NorthShore University HealthSystem, Skokie, IL 60076, USA.
Email: famirouche@northshore.org



Creative Commons Non Commercial No Derivs CC BY-NC-ND: This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs 4.0 License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>) which permits non-commercial use, reproduction and distribution of the work as published without adaptation or alteration, without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (<https://us.sagepub.com/en-us/nam/open-access-at-sage>).

to afford greater construct stability, with pedicle screws instrumentation being most commonly described.

Repositioning the patient to the prone position for placement of pedicle screws and rods can add considerable time spent in the operating room, with some authors reporting 44.4 minutes of increased operative time.⁵ Risks during posterior pedicle screw fixation include potentially violating the adjacent facet joint and, in the case of percutaneous pedicle screws, guidewire migration through the anterior vertebral body cortex, potentially leading to vascular injury.^{6,7} Percutaneous pedicle screw fixation is associated with increased surgical site pain, morbidity, intraoperative bleeding, and operative time compared to stand-alone constructs.⁸ So-called “single position surgery” has been described using robotics, intraoperative CT, or specialized bolsters for positioning and may carry a unique risk profile that has yet to be fully characterized.⁹⁻¹²

Previous biomechanical studies have highlighted the substantial stabilizing effect of extra-wide lateral interbody cages. Pimenta *et al.* reported that 26 mm LLIF cages without any supplemental fixation showed stability that exceeded transforaminal lumbar interbody fusion (TLIF) with bilateral pedicle screws and rods and 18 mm LLIF cages with unilateral screws and rods.¹³ They attributed the stability to the preservation of the posterior tension band structures and enhanced loading of the apophyseal ring. However, their study was limited to single-level fusion. The biomechanical performance of 26 mm cages for multilevel fusion has not been well characterized.

The purpose of the current study was to evaluate the biomechanical stability of extra-wide 26 mm lateral cages in a multilevel fusion construct (L1-L5, 4 levels) in flexion-extension, lateral bending, and axial rotation with unilateral or bilateral pedicle screw and rod fixation. We hypothesized that, due to the stability conferred by 26 mm wide interbody cages, the unilateral rod construct would provide similar biomechanical stability as the bilateral rod construct.

Methods

Specimen Preparation

Eight fresh-frozen human cadaveric specimens of L1-L5 were included. A priori power analysis (alpha of .05, beta of .2, power of .80) showed a minimum sample size of 6 to 8 specimens, depending on the range of motion tested. Specimens were prepared by cleaning surrounding soft tissue and muscle, taking care to preserve the discs and spinal ligaments (supraspinous, interspinous, facet capsules, posterior longitudinal ligament, and anterior longitudinal ligament). The mean specimen age was 66.5 ± 11.5 years. There were 7 male and 1 female specimens. The average BMI was 31.1 ± 7.32 kg/m². All specimens were visually inspected to confirm no fracture, deformity, previous surgery, or severe spondylosis. A CT scan (120 kV, 20 mA, .62 mm resolution, GE Brightspeed, Boston MA) was performed on all specimens to investigate the bone

quality and to produce measurements to plan optimal implant size. For testing, the sacrum and T12 vertebra were embedded in a metal cup using fast-curing resin (Bondo, fiberglass, 3M) and positioned with the L3-L4 level horizontal. Specimens were kept moisturized and wrapped in plastic foil during the curing process until tested.

Instrumentation

Lateral interbody cages were implanted with the specimen in the lateral decubitus position utilizing the LLIF surgical technique and instrumentation specific to this technique (Extreme Lateral Interbody Fusion (XLIF), Nuvasive, San Diego, California). All interbody cages were 26 mm in width (anterior-posterior dimension) and polyetheretherketone (PEEK) material (CoRoent, Nuvasive, San Diego, California). The height (superior-inferior) and length (medial-lateral) of each implant was determined by CT scan and adjusted if necessary.

Pedicle screws (Armada, Nuvasive, San Diego, California) were placed with the specimen in the prone position. Screws were implanted bilaterally at every level from L1-L5 utilizing standard freehand technique with anatomic landmarks. Screw size was determined by CT scan and adjusted if necessary. Pilot holes were tapped and probed, in addition to visual inspection of the specimens, to detect any breach. Rods were 5.5 mm titanium and placed unilaterally or bilaterally. For the unilateral rod condition, the rod was placed on the left-sided screws.

Order of Testing

Specimens were tested in the following 3 conditions: 1) intact, 2) 26 mm lateral interbody cages with unilateral rod L1-L5 (LLIF + unilateral rod), 3) 26 mm lateral interbody cages with bilateral rods L1-L5 (LLIF + bilateral rods).

Biomechanical Testing

Specimens were attached to a universal testing machine (MTS 30/G) using specially designed holding jigs. Flexion, extension, and lateral bending were attained by applying a 200 N load at a rate of 2 mm/s to the loading arm connecting the cup containing the thoracic end of the spine while the cup with the sacral end was fixed to the base of the loading frame. Axial rotation of $\pm 8^\circ$ of the specimen was achieved by coupling the thoracic end to a servo motor rotating at 2 deg/s with the sacral end fixed. A 50 N pre-load (follower load) was applied from L1 to L5. During all the tests, three-dimensional specimen motion from L1 to L5 was recorded using a motion-tracking device (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada).

Statistical Analysis

Range-of-motion measurements in flexion/extension, lateral bending, and axial rotation were measured at each segment

(L1-L2, L2-L3, L3-L4, L4-L5) and combined. Descriptive statistics were reported as mean \pm standard deviation degrees. Change in ROM after instrumentation was reported as percentage change from the intact specimen. Paired *t*-tests were used to compare ROM between instrumentation conditions. Statistical analyses were performed using Microsoft Excel Version 2013 with significance set at $P < .05$.

Results

Bone quality was determined by CT scan as previously described.¹⁴ The mean Hounsfield unit (HU) was 143 ± 29.4 (range, 84 to 169.4). Only one specimen was below the suggested threshold for osteoporosis of less than 110 HU.¹⁵

Lateral interbody cages were 26 mm in width and ranged from 8 to 14 mm. The most common heights were 10 mm ($n = 13$). Length ranged from 45 to 60 mm. The most common length was 55 mm ($n = 14$). Pedicle screw diameters ranged from 6.5 mm to 8.5 mm in diameter and 40 to 60 mm in length. The diameters of the screws implanted were 6.5 mm ($n = 10$), 7.5 mm ($n = 45$), and 8.5 mm ($n = 25$). The screw diameter was a mean $72.3 \pm 14.4\%$ (median, 70.2%) of the inner diameter of the pedicle as measured on CT scan.

Axial rotation was measured in all 8 specimens. Flexion/extension and lateral bending are presented for 7 of the specimens because of a change in methodology for acquiring these measurements.

Comparison with Intact Condition

In the intact specimen, the mean flexion-extension range of motion of each disc space was $4.95^\circ \pm 1.18^\circ$ (Table 1, Figure 1). With LLIF + unilateral rod, flexion-extension decreased by 77% to $1.12^\circ \pm .61^\circ$. With LLIF + bilateral rods, flexion-extension decreased by 83% to $.86^\circ \pm .62^\circ$. Both of these differences were statistically significant from the intact condition ($P = .0001$). Mean lateral bending was $3.65^\circ \pm 1.62^\circ$ in the intact condition. With LLIF + unilateral rod, lateral bending decreased by 53% to $1.73^\circ \pm .97^\circ$. With LLIF + bilateral rods, lateral bending decreased by 64% to $1.3^\circ \pm .86^\circ$. Both of these differences were statistically significant from the intact condition ($P < .0003$).

For axial rotation, the intact specimen mean ROM was $1.4^\circ \pm .62^\circ$. With LLIF + unilateral rod, axial rotation decreased 26% to $1.04^\circ \pm .63^\circ$. With LLIF + bilateral rods, axial rotation decreased 34% to $.93^\circ \pm .55^\circ$. The difference was statistically significant only for LLIF + bilateral rods ($P = .01$).

Table 1. Comparison of range-of-motion of intact spine specimens with specimens after lumbar lateral interbody fusion (LLIF) with unilateral or bilateral pedicle screw and rod fixation.

Level	Intact Specimen		LLIF + Unilateral Rod			LLIF + Bilateral Rods		
	Average	SD	Average	SD	^a P-value	Average	SD	^a P-value
L1-L2	4.49	.87	1.19	.47	<.001	.80	.39	<.001
L2-L3	5.47	1.09	.73	.45	<.001	.42	.25	<.001
L3-L4	4.09	.58	1.00	.81	<.001	.71	.66	<.001
L4-L5	5.76	2.18	1.57	.69	<.001	1.52	1.18	.005
Combined value (N = 28)	4.95	1.18	1.12	.61	<.001	.86	.62	<.001
% Decrease from intact			77%			83%		
Lateral bending (Degrees)								
L1-L2	3.27	1.07	1.32	.76	.003	.97	.77	.001
L2-L3	2.09	.89	1.07	.52	.057	.47	.27	.004
L3-L4	3.03	1.81	1.54	1.18	.038	1.13	.88	.012
L4-L5	6.22	2.69	3.00	1.40	.005	2.64	1.52	.001
Combined value (N = 28)	3.65	1.62	1.73	.97	<.001	1.30	.86	<.001
% Decrease from intact			53%			64%		
Axial rotation (Degrees)								
L1-L2	.70	.52	1.09	.88	.360	1.07	.88	.390
L2-L3	1.52	.57	.96	.35	.030	.84	.25	.010
L3-L4	1.73	.75	.68	.36	.560	.61	.25	<.001
L4-L5	1.67	.66	1.44	.93	.360	1.20	.82	.220
Combined value (N = 28)	1.40	.62	1.04	.63	.285	.93	.55	.011
% Decrease from intact			26%			34%		

^aCompared to intact specimen using paired *t*-tests.

Comparison between Unilateral and Bilateral Rods

Comparing LLIF + unilateral rod and LLIF + bilateral rods, LLIF + bilateral rods had 23% less range of motion in flexion-extension, 25% less range of motion in lateral bending, and 11% less range of motion in axial rotation. (Table 2) The differences were statistically significant for flexion-extension and lateral bending ($P \leq .003$). The difference did not reach statistical significance for axial rotation ($P = .07$).

Discussion

The Current Study

Revealed that, after multilevel placement of 26 mm lateral interbody cages, bilateral pedicle screw and rod fixation showed statistically significant reductions in flexion-extension and lateral bending motions compared to unilateral rod fixation. Bilateral screws and rods also demonstrated lower axial rotation than unilateral screws and rods, although the difference did not reach statistical significance. Despite the purported biomechanical advantages conferred by the lateral interbody technique and extra wide (26 mm) cages, the addition of bilateral posterior instrumentation nevertheless showed demonstrably higher stability, defined here as a lower ROM. It should be noted that the results reflect differences in

ROM, rather than construct stiffness; however, values of intervertebral displacement are valuable as they are indicative of the resistance that is provided by the structure's stiffness.

Lateral interbody fusion performed with transpsoas or anterior to psoas access is biomechanically favorable due to the approach. Lateral access of the disc preserves the posterior tension band that is disrupted with posterior-based interbody fusion, which imparts increased stability.¹⁶ The anterior longitudinal ligament (ALL) is a significant stabilizer of the spinal column, which is resected during anterior-based interbody fusion but is preserved with LLIF.^{17,18} Combining LLIF with open posterior techniques for adult deformity surgery has been reported to have decreased complications, faster recovery, and fewer levels fused compared to the use of all-posterior techniques.¹⁹

The large footprint of LLIF cages provides enhanced loading of the apophyseal ring. Subsidence has been associated with cage width < 22 mm and cage height >11 mm, osteoporosis, and multilevel surgery.²⁰ Lang *et al.* reported a near-complete elimination of late subsidence with the use of extra-wide 26 mm cages.²¹ A biomechanical study of single-level interbody fusion by Pimenta *et al.* compared the stabilizing effect of 26 mm LLIF cages, 18 mm LLIF cages, and TLIF cages either stand-alone or combined with bilateral or unilateral pedicle screw-rod fixation.¹³ They found that stand-

Table 2. Comparison of range-of-motion of specimens after lumbar lateral interbody fusion (LLIF) with unilateral or bilateral pedicle screw and rod fixation.

Flexion-Extension (Degrees)						
Level	LLIF + Unilateral Rod		LLIF + Bilateral Rods		Paired t-test ^a P-value	
	Average	SD	Average	SD		
L1-L2	1.19	.47	.80	.39	.004	
L2-L3	.73	.45	.42	.25	.026	
L3-L4	1.00	.81	.71	.66	.024	
L4-L5	1.57	.69	1.52	1.18	.500	
Combined value (N = 28)	1.12	.61	.86	.62	.015	
% Decrease from LLIF + Unilateral rod	23%					
Lateral bending (Degrees)						
L1-L2	1.32	.76	.97	.77	.158	
L2-L3	1.07	.52	.47	.27	.002	
L3-L4	1.54	1.18	1.13	.88	.051	
L4-L5	3.00	1.40	2.64	1.52	.224	
Combined value (N = 28)	1.73	.97	1.30	.86	.003	
% Decrease from LLIF + Unilateral rod	25%					
Axial rotation (Degrees)						
L1-L2	1.09	.88	1.07	.88	.345	
L2-L3	.96	.35	.84	.25	.079	
L3-L4	.68	.36	.61	.25	.176	
L4-L5	1.44	.93	1.20	.82	.156	
Combined value (N = 28)	1.04	.63	.93	.55	.071	
% Decrease from LLIF + Unilateral rod	11%					

^aCompared to intact specimen using paired t-tests.

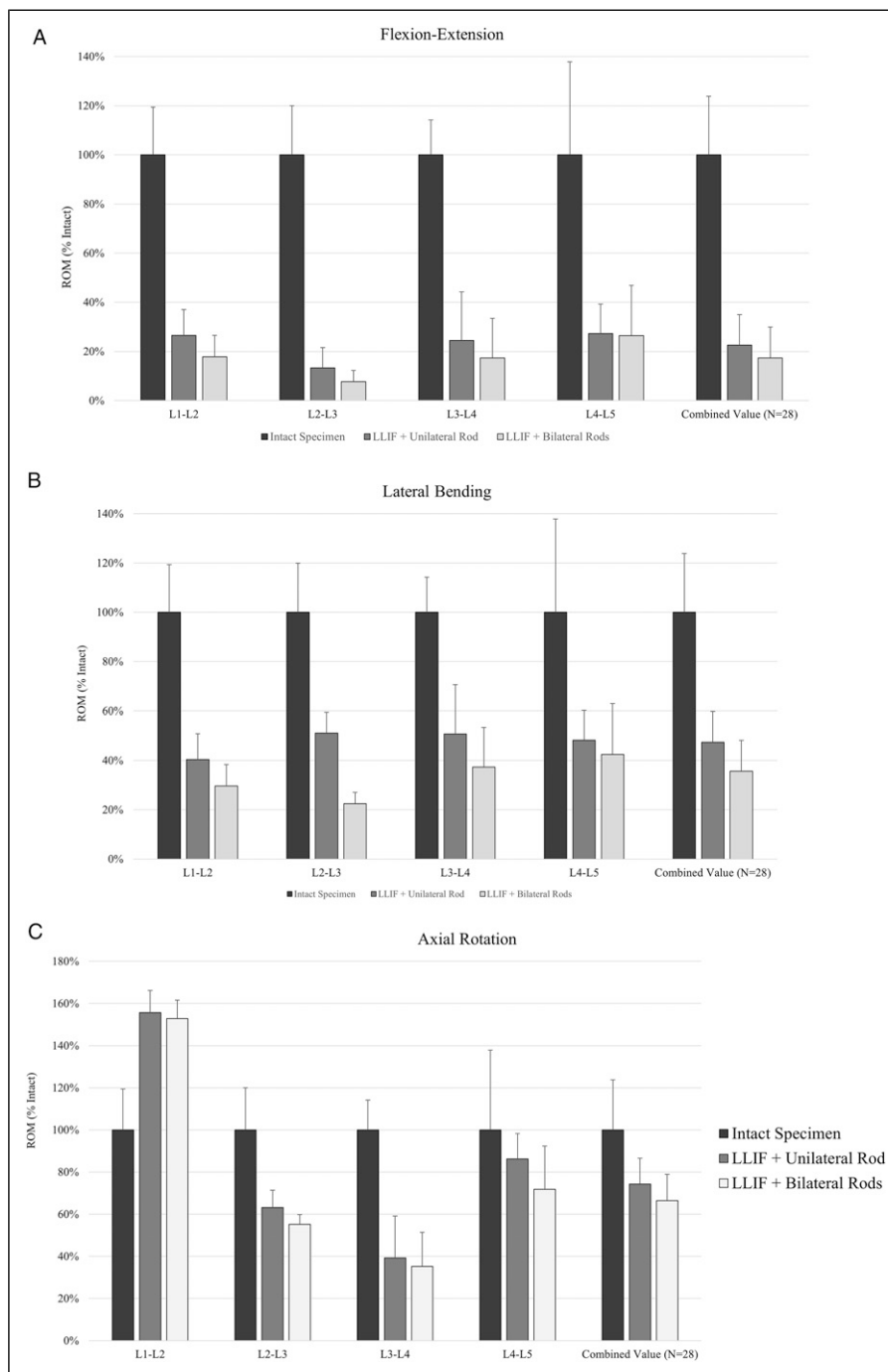


Figure 1. Bar graphs depicting the range-of-motion achieved by the intact spine specimen and specimens instrumented with lumbar lateral interbody (LLIF) cages with unilateral and bilateral pedicle screw and rod fixation. Range-of-motion was compared in A) flexion-extension, B) lateral bending, and C) axial rotation. Paired t-test: * $P < .05$, ** $P < .01$, *** $P < .001$.

alone 26 mm cages demonstrated statistically greater stability in axial rotation and similar stability in flexion-extension and lateral bending as TLIF with bilateral pedicle screws and rods. This highlights the biomechanical importance of preserving the posterior tension band, which is removed with posterior-based open and minimally invasive interbody

fusion techniques.²² In addition, the stand-alone 26 mm LLIF cage construct was statistically more stable in axial rotation, flexion-extension, and lateral bending than the 18 mm LLIF cage with unilateral posterior supplemental fixation. This study demonstrated the substantial stability conferred by the greater apophyseal ring engagement of 26 mm cages, even in

the stand-alone condition. Based on these findings, we hypothesized that unilateral rod fixation would provide similar biomechanical stability as bilateral screws and rods in a multilevel LLIF model utilizing extra-wide 26 mm cages.

Unilateral, as opposed to bilateral, pedicle screw and rod instrumentation as supplemental posterior fixation has important advantages including decreased blood loss, decreased operating room time, and short-term improvement in post-operative pain.²³⁻²⁶ Multiple large series of patients undergoing TLIF have reported lower cost and equivalent clinical outcomes with unilateral screw and rod fixation, although rates of non-union and cage migration may be higher.²⁴⁻²⁶

The use of unilateral pedicle screw fixation for LLIF has been described with good clinical and radiographic results. Wen *et al.* retrospectively compared 74 patients undergoing single-level LLIF supplemented with either unilateral or bilateral screw fixation and reported significantly decreased medical expenses (\$11,044.80 vs \$15,018.40) and lower Oswestry Disability Index (ODI) and visual analog pains scores (VAS) at 7-days postoperatively in the unilateral fixation group.²⁷ Unilateral screw fixation did not affect rates of fusion (86.8% vs. 91.7%) or cage subsidence. A prospective cohort study by Fukushima *et al.* of 100 patients similarly found shorter operative times with unilateral screw fixation with equivalent fusion rates (87.8% vs 84.7%) and subsidence rates between the study groups.²⁸ However, there was a higher rate (5 cases vs. 1 case) of reoperation in the unilateral screw group mostly due to cage loosening. A 20-patient case series by Du *et al.* reported excellent radiographic and clinical outcomes for single-level adjacent segment disease treated with LLIF and unilateral screw fixation.²⁹ Collectively, these studies suggest that unilateral screw fixation for LLIF in single-level disease may be sufficient.

We are not aware of any clinical reports of unilateral screw fixation after multilevel LLIF. If this is found to be an acceptable surgical strategy, the benefits of unilateral fixation in terms of time savings and decreased morbidity^{30,31} could potentially be amplified in the setting of multilevel LLIF. The use of unilateral fixation could facilitate single-position surgery, in which the patient remains in the lateral decubitus position after LLIF and pedicle screws are placed in this position. The technical feasibility of percutaneously instrumenting one side of the spine in the lateral position (usually the superior side) is considerably less challenging than bilateral instrumentation. The perceived need to place bilateral pedicle screws and rods has given rise to the concept of single position LLIF surgery in the prone position. However, the potential complications of placing only unilateral constructs (e.g., pseudoarthrosis, late deformity, decreased correction, etc.) could be multiplied in multilevel LLIF, so characterization of the biomechanical properties is critical.

Previous biomechanical studies on unilateral fixation after LLIF have been limited to single-level fusion and/or narrow interbody cages (18 mm or less in width). We chose 26 mm cages in a 4-level LLIF model because the extra wide cages

possess important biomechanical advantages.¹³ Godzik *et al.* evaluated single-level LLIF at L2-3 or L3-4 with unilateral and bilateral pedicle screw fixation in 13 human specimens utilizing 18 mm cages.³² They reported statistically similar stiffness in flexion-extension, lateral bending, and axial rotation. A similar study from the same institution by Reis *et al.* evaluated LLIF in seven cadaveric specimens at L3-4 combined with multiple supplemental fixation methods.³³ The bilateral pedicle screw fixation construct afforded a 91% decrease in flexion, 82% decrease in extension and lateral bending, and 74% decrease in axial rotation compared with intact specimens. They reported a significant decrease in stability with unilateral screw fixation, which was roughly one-half the stiffness of bilateral screw fixation. Our findings were similar in the multilevel setting, in which we observed an 83% decrease in flexion-extension, 64% decrease in lateral bending, and 34% decrease in axial rotation with bilateral screws and rods, as well as significant decreases in construct stiffness with unilateral screw fixation. A multilevel LLIF cadaveric study utilizing 17 mm wide cages by Lai *et al.* tested six T12-L5 human specimens with LLIF at L2-5 combined with either unilateral screws, bilateral screws, or lateral plate fixation.³⁴ The authors found bilateral pedicle screw fixation significantly reduced overall lumbar motion in flexion-extension (3° vs. 5.93°), lateral bending (3.69° vs. 7.37°), and axial rotation (6.46° vs. 9.82°) compared to unilateral screws. Nevertheless, they concluded that unilateral screw or plate fixation may provide sufficient biomechanical stability for multilevel LLIF. The reported reductions in ROM are larger than our results, which may be attributable to differences in experimental technique and the notably high baseline ROM of the intact specimens reported by Lai *et al.* We utilized a high proportion (87.5%) of relatively large diameter 7.5 and 8.5 mm screws. Screw diameter has been shown to have a significant effect on stiffness.³⁵

In conclusion, we observed considerable decreases in ROM from the intact condition after 4-level LLIF utilizing 26 mm cages for both unilateral and bilateral pedicle screws and rods. The addition of bilateral posterior fixation provides a 10-25% additional decrease in ROM. The stability afforded by unilateral screws and rods after multilevel LLIF may be adequate to achieve a solid arthrodesis for select patients, such as those with minimal risk factors for cage subsidence or non-union. The results of this study can inform surgeons as they consider unilateral or bilateral posterior fixation regarding the incremental biomechanical benefit that can be expected from additional instrumentation. Our results concluded that the construct with maximum stability, regardless of the use of extra-wide cages, remains LLIF with bilateral screws and rods.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Drs. James Mok and Farid Amirouche disclose in-kind

product donation by Nuvasive. Dr. James Mok discloses that he receives consulting fees and royalties from MiRus. Drs. Craig Forsthoefel, Roberto Leonardo Diaz, and Ye Lin have nothing to disclose.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Roberto Leonardo Diaz  <https://orcid.org/0000-0003-2595-1390>
Farid Amirouche  <https://orcid.org/0000-0002-3002-4199>

References

1. Woods KRM, Billys JB, Hynes RA. Technical description of oblique lateral interbody fusion at L1-L5 (OLIF25) and at L5-S1 (OLIF51) and evaluation of complication and fusion rates. *Spine J*. 2017;17(4):545-553. doi:10.1016/j.spinee.2016.10.026
2. Ohiorhenuan IE, Martirosyan NL, Wewel JT, Sagar S, Uribe JS. Lateral Interbody Fusion at L4/5: Management of the Transitional Psoas. *World Neurosurg*. 2021;148:e192-e196. doi:10.1016/j.wneu.2020.12.105
3. Abel NA, Januszewski J, Vivas AC, Uribe JS. Femoral nerve and lumbar plexus injury after minimally invasive lateral retroperitoneal transpsoas approach: electrodiagnostic prognostic indicators and a roadmap to recovery. *Neurosurg Rev*. 2018;41(2):457-464. doi:10.1007/s10143-017-0863-7
4. Pham MH, Hassan O, Diaz-Aguilar LD, Lehman RA. Complications Associated With Oblique Lumbar Interbody Fusion at L5-S1: A Systematic Review of the Literature. *Neurosurg Open*. 2021;2(3):11. doi:10.1093/neuopen/okab018
5. Ziino C, Konopka JA, Ajiboye RM, Ledesma JB, Koltsov JCB, Cheng I. Single position versus lateral-then-prone positioning for lateral interbody fusion and pedicle screw fixation. *J spine Surg (Hong Kong)*. 2018;4(4):717-724. doi:10.21037/jss.2018.12.03
6. Patel RD, Graziano GP, Vanderhave KL, Patel AA, Gerling MC. Facet violation with the placement of percutaneous pedicle screws. *Spine (Phila Pa)*. 2011;36(26):E1749-E1752. doi:10.1097/BRS.0b013e318221a800
7. Mobbs RJ, Raley DA. Complications with K-wire insertion for percutaneous pedicle screws. *J Spinal Disord Tech*. 2014;27(7):390-394. doi:10.1097/BSD.0b013e3182999380
8. Zhao Q, Zhang H, Hao D, Guo H, Wang B, He B. Complications of percutaneous pedicle screw fixation in treating thoracolumbar and lumbar fracture. *Medicine (Baltimore)*. 2018;97(29):e11560. doi:10.1097/MD.00000000000011560
9. Walker CT, Farber SH, Gandhi S, Godzik J, Turner JD, Uribe JS. Single-Position Prone Lateral Interbody Fusion Improves Segmental Lordosis in Lumbar Spondylolisthesis. *World Neurosurg*. 2021;151:e786-e792. doi:10.1016/j.wneu.2021.04.128
10. Pham MH, Diaz-Aguilar LD, Shah V, Brandel M, Loya J, Lehman RA. Simultaneous robotic single position oblique lumbar interbody fusion with bilateral sacropelvic fixation in lateral decubitus. *Neurospine*. 2021;18(2):406-412. doi:10.14245/ns.2040774.387
11. Diaz-Aguilar LD, Shah V, Himstead A, Brown NJ, Abraham ME, Pham MH. Simultaneous robotic single-position surgery (SR-SPS) with Oblique lumbar interbody fusion: a case series. *World Neurosurg*. 2021;151:e1036-e1043. doi:10.1016/j.wneu.2021.05.043
12. Pimenta L, Pokorny G, Amaral R, et al. Single-Position Prone Transpsoas Lateral Interbody Fusion Including L4L5: Early Postoperative Outcomes. *World Neurosurg*. 2021;149:e664-e668. doi:10.1016/j.wneu.2021.01.118
13. Pimenta L, Turner AWL, Dooley ZA, Parikh RD, Peterson MD. Biomechanics of lateral interbody spacers: going wider for going stiffer. *Sci World J*. 2012;2012:381814-381816. doi:10.1100/2012/381814
14. Anderson PA, Polly DW, Binkley NC, Pickhardt PJ. Clinical Use of Opportunistic Computed Tomography Screening for Osteoporosis. *J Bone Joint Surg Am*. 2018;100(23):2073-2081. doi:10.2106/JBJS.17.01376
15. Lee SJ, Binkley N, Lubner MG, Bruce RJ, Ziemlewicz TJ, Pickhardt PJ. Opportunistic screening for osteoporosis using the sagittal reconstruction from routine abdominal CT for combined assessment of vertebral fractures and density. *Osteoporos Int*. 2016;27(3):1131-1136. doi:10.1007/s00198-015-3318-4
16. Ozgur BM, Aryan HE, Pimenta L, Taylor WR. Extreme Lateral Interbody Fusion (XLIF): a novel surgical technique for anterior lumbar interbody fusion. *Spine J*. 2006;6(4):435-443. doi:10.1016/j.spinee.2005.08.012
17. Demirkiran G, Theologis AA, Pekmezci M, Ames C, Deviren V. Adult Spinal Deformity Correction with Multi-level Anterior Column Releases: Description of a New Surgical Technique and Literature Review. *Clin spine Surg*. 2016;29(4):141-149. doi:10.1097/BSD.0000000000000377
18. Park J-S, Lee C-S, Choi Y-T, Park S-J. Usefulness of anterior column release for segmental lordosis restoration in degenerative lumbar kyphosis. *J Neurosurg Spine*. 2022;36:1-7. doi:10.3171/2021.5.SPINE202196
19. Strom RG, Bae J, Mizutani J, Valone F, Ames CP, Deviren V. Lateral interbody fusion combined with open posterior surgery for adult spinal deformity. *J Neurosurg Spine*. 2016;25(6):697-705. doi:10.3171/2016.4.SPINE16157
20. Wu H, Shan Z, Zhao F, Cheung JPY. Poor Bone Quality, Multilevel Surgery, and Narrow and Tall Cages Are Associated with Intraoperative Endplate Injuries and Late-onset Cage Subsidence in Lateral Lumbar Interbody Fusion: A Systematic Review. *Clin Orthop Relat Res*. 2022;480(1):163-188. doi:10.1097/CORR.0000000000001915
21. Lang G, Navarro-Ramirez R, Gandevia L, et al. Elimination of Subsidence with 26-mm-Wide Cages in Extreme Lateral Interbody Fusion. *World Neurosurg*. 2017;104:644-652. doi:10.1016/j.wneu.2017.05.035
22. Holly LT, Schwender JD, Rouben DP, Foley KT. Minimally invasive transforaminal lumbar interbody fusion: indications, technique, and complications. *Neurosurg Focus*. 2006;20(3):E6. doi:10.3171/foc.2006.20.3.7

23. Ren C, Qin R, Sun P, Wang P. Effectiveness and safety of unilateral pedicle screw fixation in transforaminal lumbar interbody fusion (TLIF): a systematic review and meta-analysis. *Arch Orthop Trauma Surg.* 2017;137(4):441-450. doi:10.1007/s00402-017-2641-y
24. Liu F, Feng Z, Zhou X, et al. Unilateral Versus Bilateral Pedicle Screw Fixation in Transforaminal Lumbar Interbody Fusion: A Monocentric Study of 215 Patients With a Minimum of 4-Year Follow-up. *Clin spine Surg.* 2017;30(6):E776-E783. doi:10.1097/BSD.0000000000000416
25. Choi UY, Park JY, Kim KH, Kuh SU, Chin DK, Unilateral versus bilateral percutaneous pedicle screw fixation in minimally invasive transforaminal lumbar interbody fusion. *Neurosurg Focus.* 2013; 35(2):E11. doi:10.3171/2013.2.FOCUS12398
26. Badikillaya V, Akbari KK, Sudarshan P, Suthar H, Venkatesan M, Hegde SK. Comparative Analysis of Unilateral versus Bilateral Instrumentation in TLIF for Lumbar Degenerative Disorder: Single Center Large Series. *Int J Spine Surg.* 2021;15(5): 929-936. doi:10.14444/8121
27. Wen J, Shi C, Yu L, Wang S, Xi Y, Ye X. Unilateral Versus Bilateral Percutaneous Pedicle Screw Fixation in Oblique Lumbar Interbody Fusion. *World Neurosurg.* 2020;134: e920-e927. doi:10.1016/j.wneu.2019.11.035
28. Fukushima M, Oshima Y, Yuzawa Y, Tanaka S, Inanami H. Clinical and radiographic analysis of unilateral versus bilateral instrumented one-level lateral lumbar interbody fusion. *Sci Rep.* 2020;10(1):3105. doi:10.1038/s41598-020-59706-9
29. Du JY, Kiely PD, Al Maaieh M, Aichmair A, Huang RC. Lateral lumbar interbody fusion with unilateral pedicle screw fixation for the treatment of adjacent segment disease: a preliminary report. *J spine Surg (Hong Kong).* 2017;3(3):330-337. doi:10.21037/jss.2017.06.17
30. Warren SI, Wadhwa H, Koltsov JCB, Michaud JB, Cheng I. One surgeon's learning curve with single position lateral lumbar interbody fusion: perioperative outcomes and complications. *J Spine Surg.* 2021;7(2):162-169. doi:10.21037/jss-21-13
31. Wen J, Shi C, Yu L, Wang S, Xi Y, Ye X. Unilateral Versus Bilateral Percutaneous Pedicle Screw Fixation in Oblique Lumbar Interbody Fusion. *World Neurosurg.* 2020;134: e920-e927. doi:10.1016/j.wneu.2019.11.035
32. Godzik J, Martinez-Del-Campo E, Newcomb AGUS, et al. Biomechanical Stability Afforded by Unilateral Versus Bilateral Pedicle Screw Fixation with and without Interbody Support Using Lateral Lumbar Interbody Fusion. *World Neurosurg.* 2018;113:e439-e445. doi:10.1016/j.wneu.2018.02.053
33. Reis MT, Reyes PM, Altun I, et al. Biomechanical evaluation of lateral lumbar interbody fusion with secondary augmentation. *J Neurosurg Spine.* 2016;25(6):720-726. doi:10.3171/2016.4.SPINE151386
34. Lai O, Chen Y, Chen Q, Hu Y, Ma W. Cadaveric biomechanical analysis of multilevel lateral lumbar interbody fusion with and without supplemental instrumentation. *BMC Musculoskelet Disord.* 2021;22(1):280. doi:10.1186/s12891-021-04151-6
35. Matsukawa K, Yato Y, Imabayashi H. Impact of Screw Diameter and Length on Pedicle Screw Fixation Strength in Osteoporotic Vertebrae: A Finite Element Analysis. *Asian Spine J.* 2021; 15(5):566-574. doi:10.31616/asj.2020.0353