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Biomechanical Analysis of Cortical Versus Pedicle Screw Fixation Stability in TLIF, PLIF, and XLIF Applications

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Abstract

Study Design: Cadaveric biomechanical study.

Objectives: Medial-to-lateral trajectory cortical screws are of clinical interest due to the ability to place them through a less disruptive, medialized exposure compared with conventional pedicle screws. In this study, cortical and pedicle screw trajectory stability was investigated in single-level transforaminal lumbar interbody fusion (TLIF), posterior lumbar interbody fusion (PLIF), and extreme lateral interbody fusion (XLIF) constructs.

Methods: Eight lumbar spinal units were used for each interbody/screw trajectory combination. The following constructs were tested: TLIF + unilateral facetectomy (UF) + bilateral pedicle screws (BPS), TLIF + UF + bilateral cortical screws (BCS), PLIF + medial facetectomy (MF) + BPS, PLIF + bilateral facetectomy (BF) + BPS, PLIF + MF + BCS, PLIF + BF + BCS, XLIF + BPS, XLIF + BCS, and XLIF + bilateral laminotomy + BCS. Range of motion (ROM) in flexion-extension, lateral bending, and axial rotation was assessed using pure moments.

Results: All instrumented constructs were significantly more rigid than intact ($P < .05$) in all test directions except TLIF + UF + BCS, PLIF + MF + BCS, and PLIF + BF + BCS in axial rotation. In general, XLIF and PLIF + MF constructs were more rigid (lowest ROM) than TLIF + UF and PLIF + BF constructs. In the presence of substantial iatrogenic destabilization (TLIF + UF and PLIF + BF), cortical screw constructs tended to be less rigid (higher ROM) than the same pedicle screw constructs in lateral bending and axial rotation; however, no statistically significant differences were found when comparing pedicle and cortical fixation for the same interbody procedures.

Conclusions: Both cortical and pedicle trajectory screw fixation provided stability to the 1-level interbody constructs. Constructs with the least iatrogenic destabilization were most rigid. The more destabilized constructs showed less lateral bending and axial rotation rigidity with cortical screws compared with pedicle screws. Further investigation is warranted to understand the clinical implications of differences between constructs.

Keywords
screw fixation, screw trajectory, lumbar interbody fusion, cortical screw

Introduction

Segmental pedicle screw-rod fixation, pioneered by Roy-Camille[1] and modified by Weinstein,[2] is considered the gold standard for internal stabilization of the thoracolumbar spine. Complications with pedicle screws include superior facet violation and morbidity associated with soft tissue dissection. Superior facet violation may accelerate degenerative changes.[2-6] Dissection of the paraspinal muscles is needed as far lateral as the transverse processes. The multifidus muscle is

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considered especially vulnerable due to its monosegmental innervation.[7-9] Segmental nerve injury may lead to muscle atrophy, segmental instability, disc degeneration, and herniation.[10,11]

Medial-to-lateral trajectory cortical screws have been proposed as an alternative to conventional pedicle screws as the medial screw entry point allows for less disruptive dissection, only as far lateral as the pars, in order to introduce the fixation and reduced likelihood of facet violation. Cortical screws have been described in clinical applications for posterior approaches such as transforaminal lumbar interbody fusion (TLIF) and posterior lumbar interbody fusion (PLIF).[12-18] In addition, cortical screws may be appropriate to provide internal stabilization to a transpsoas lateral lumbar interbody fusion (extreme lateral interbody fusion [XLIF]/lateral lumbar interbody fusion) where posterior fixation via a mini-open rather than a percutaneous approach is preferred, or when direct decompression is needed.

The increased proportion of cortical bone along the screw trajectory and use of cortical thread forms may also offer improved screw fixation strength. There is an increasing number of biomechanical studies examining the stability provided by cortical screws for thoracolumbar spinal fixation. Screw toggle and pullout,[19-24] screw insertion torque,[21,25,26] single-level construct stability,[27,28] and multievel construct stability[29] using cortical screws have been investigated. While the stability of TLIF and XLIF constructs with pedicle and cortical screws has been investigated, the stability of PLIF constructs has not yet been reported. Furthermore, the biomechanical effect of extent of PLIF decompression and the consequence of XLIF direct decompression are also unknown. Finally, TLIF, PLIF, and XLIF constructs have not all been compared within the same analysis. In this lumbar cadaveric study, the multidirectional stability of bilateral medial-to-lateral trajectory cortical screw constructs and conventional trajectory pedicle screw constructs were compared when providing supplemental fixation to single-level TLIF, PLIF, or XLIF constructs.

Table 1. Test Conditions.

Interbody	Posterior Decompression	Fixation	Condition Name
TLIF	Unilateral facetectomy	Bilateral pedicle screws	TLIF + UF + BPS
	Unilateral facetectomy	Bilateral cortical screws	TLIF + UF + BCS
PLIF	Medial facetectomy	Bilateral pedicle screws	PLIF + MF + BPS
	Bilateral facetectomy	Bilateral pedicle screws	PLIF + BF + BPS
	Medial facetectomy	Bilateral cortical screws	PLIF + MF + BCS
	Bilateral facetectomy	Bilateral cortical screws	PLIF + BF + BCS
XLIF	None	Bilateral pedicle screws	XLIF + BPS
	None	Bilateral cortical screws	XLIF + BCS
	Bilateral laminotomy	Bilateral cortical screws	XLIF + BL + BCS

Abbreviations: TLIF, transforaminal lumbar interbody fusion; UF, unilateral facetectomy; BPS, bilateral pedicle screw; BCS, bilateral cortical screw; PLIF, posterior lumbar interbody fusion; MF, medial facetectomy; BF, bilateral facetectomy; XLIF, extreme lateral interbody fusion; BL, bilateral laminotomy.

Materials and Methods

Test Conditions

Specimens were initially tested intact. TLIF, PLIF, and XLIF interbody constructs were then tested with bilateral pedicle and cortical screw-rod fixation under the conditions listed in Table 1.

Specimen Preparation

Fresh frozen cadaver spines from T12 to the sacrum were obtained. Muscle tissue was removed, while ligament and disc tissue were retained. Spines were subjected to dual-energy X-ray absorptiometry (DEXA) scanning (Discovery C, Hologic, Inc, Bedford, MA) to rule out osteoporotic specimens and for specimen grouping, and A-P and lateral fluoroscopy to exclude deformity and significant degeneration. Two motion segments from each specimen (L1-2 and L3-4 in half of the specimens and L2-3 and L4-5 in the remaining specimens) were tested resulting in 8 constructs for each interbody and screw trajectory combination (TLIF with pedicle screws, TLIF with cortical screws, PLIF with pedicle screws, PLIF with cortical screws, XLIF with pedicle screws, and XLIF with cortical screws). Numerous studies have tested constructs with different levels from the same or different specimens.[30-34] Bone mineral density (BMD) was matched between groups. Cephalad and caudal specimen ends were potted in polyurethane resin (Smooth-Cast, Smooth-On, Inc, Easton, PA).

Surgical Procedures

Screw Fixation. Bilateral pedicle screws (BPS; Precept Pedicle Screw System, NuVasive, Inc, San Diego, CA) were placed along a conventional lateral-to-medial trajectory.[2] Screw diameters were Ø5.5 to 7.5 mm with lengths of 40 to 55 mm. Bilateral cortical screws (BCS; Precept Pedicle Screw System) were placed using a medial-to-lateral technique.[22] Screws diameters were all Ø5.0 mm with lengths of 30 to 35 mm.

Interbody and Posterior Decompression. TLIF specimens received a complete unilateral facetectomy (UF) and single interbody cage with 10 × 25 mm, 10 × 30 mm, or 10 × 35 mm footprint sizes (CoRoent LO, NuVasive, Inc) delivered along an oblique trajectory. PLIF specimens initially received medial facetectomies (MFs) that included bilateral resection of the medial aspect of the inferior articular processes. Bilateral interbody cages with 9 × 23 mm or 9 × 28 mm footprint sizes (CoRoent LMP, NuVasive, Inc) were delivered as far lateral as possible. Subsequently, complete bilateral facetectomies (BFs) were performed, whereby the articular processes were removed. XLIF specimens received laterally applied interbody cages with 18 × 50 mm or 18 × 55 mm footprint sizes (CoRoent XL, NuVasive, Inc) spanning the apophyseal ring. Cortical screw constructs initially had no posterior decompression; then, a bilateral laminotomy (BL) was performed, while pedicle screw constructs were only tested with intact posterior elements.

Biomechanical Testing

For each test condition, specimens were mounted on a custom 6 degrees of freedom spine test system described previously.[35] The loading protocol consisted of 3 cycles of pure, unconstrained moments to ±7.5 N m in each motion direction (flexion-extension, lateral bending, and axial rotation) without axial preload.[36,37] Motion was recorded across each tested level using infrared LED arrays attached to the vertebrae immediately cephalad and caudal to the interbody implant. The LEDs were tracked using an optoelectronic motion capture system (Optotrak Certus, Northern Digital, Inc, Waterloo, Ontario, Canada).

Data Analysis

Data from the third loading cycle in each test direction was analyzed. Range of motion (ROM) was normalized to intact. BMD and intact ROM were compared across all groups using 1-way analysis of variance. Normalized ROM of instrumented conditions were compared using 1-way analysis of variance and Tukey-Kramer post hoc comparisons, with $P \leq .05$ considered significant.

Results

Average BMD was 0.897 g/cm^2 (range = 0.767-1.089 g/cm^2) for the PLIF specimens, 0.897 g/cm^2 (range = 0.750-1.081 g/cm^2) for the TLIF specimens, and 0.868 g/cm^2 (range = 0.695-1.053 g/cm^2) for the XLIF specimens. This was not found to be statistically significantly different between groups ($P = .871$). Average intact ROM for all groups in flexion-extension was 7.1 ± 2.6°, in lateral bending 8.1 ± 3.4°, and in axial rotation 2.9 ± 1.6°. There were no significant differences in intact ROM for any of the test groups (flexion-extension: $P = .903$, lateral bending: $P = .706$, axial rotation: $P = .970$).

Comparing the instrumented constructs with intact (Figure 1), there was a significant ($P \leq .05$) reduction in ROM for all TLIF, PLIF, and XLIF reconstructions in flexion-extension and lateral bending, with all producing less than 38.8% intact ROM. In axial rotation, all constructs significantly reduced ROM with regard to intact except TLIF + UF + BCS (88.6 ± 35.6% intact ROM), PLIF + MF + BCS (64.5 ± 24.0% intact ROM), and PLIF + BF + BCS (95.2 ± 32.3% intact ROM). Despite relatively modest average percent reductions in axial rotation ROM with regard to intact for these conditions, initial intact axial rotation ROM was much smaller than the other loading directions, and the instrumented ROM (in degrees) was lower than in lateral bending for the same constructs.

Evaluating the instrumented conditions, the most rigid construct (lowest ROM) in flexion-extension was XLIF + BL + BCS (8.8 ± 2.8%), and in lateral bending and axial rotation was XLIF + BPS (14.2 ± 5.2% and 38.7 ± 13.8%, respectively). Conversely, the least rigid (greatest ROM) construct in flexion-extension and axial rotation was PLIF + BF + BCS (20.2 ± 10.4% and 95.2 ± 32.3%, respectively), and in lateral bending it was TLIF + UF + BCS (38.8 ± 17.8%). Statistical analysis revealed that in flexion-extension XLIF + BCS, XLIF + BL + BCS, and PLIF + MF + BPS were significantly more rigid ($P \leq .025$) than PLIF + BF + BCS. In lateral bending, XLIF + BPS and PLIF + MF + BPS were both significantly more rigid than TLIF + UF + BCS ($P \leq .023$) as well as PLIF + BF + BCS ($P \leq .045$). Likewise in axial rotation, XLIF + BPS and PLIF + MF + BPS were both significantly more rigid than TLIF + UF + BCS ($P \leq .015$) as well as PLIF + BF + BCS ($P \leq 0.002$). Additionally, XLIF + BCS was significantly more rigid than PLIF + BF + BCS ($P = .050$).

Comparing the interbody constructs with pedicle screw fixation, no statistically significant differences were detected ($P \geq .605$); however, generally XLIF provided the lowest ROM, followed by PLIF + MF and then TLIF + UF/PLIF + BL. Comparing interbody constructs with cortical screw fixation, XLIF with or without BL was more rigid than PLIF + BF in flexion-extension ($P \leq 0.007$), and XLIF without BL was more rigid than PLIF + BF in axial rotation ($P = .050$), with no differences in lateral bending ($P \geq .614$). Again, generally XLIF provided the lowest ROM, followed by PLIF + MF and then TLIF + UF/PLIF + BL. Last, comparing pedicle and cortical fixation for the same interbody procedures, no statistically significant differences were found ($P \geq .130$).

Discussion

Medial-to-lateral trajectory cortical screws potentially offer an alternative thoracolumbar fixation option for interbody fusion techniques. In the current study, the XLIF and PLIF constructs retaining bilateral facet joints provided the most rigid stability. TLIF with UF and PLIF with BF were similar and both allowed more motion. The finding that XLIF is more stable than TLIF has been reported previously, attributable to the lack of iatrogenic destabilization and large buttressing interbody spacer with XLIF.[28,38] XLIF has not to our knowledge previously been compared with PLIF and was found here to have similar ROM provided only MFs were performed. PLIF has previously been shown to be more stable than TLIF, consistent with this study, again if most facet joint integrity is retained.[39,40] After bilateral facet resection, this study showed equivalent ROM for TLIF and PLIF in all directions. The relative stability of the various interbody constructs was found to be consistent when

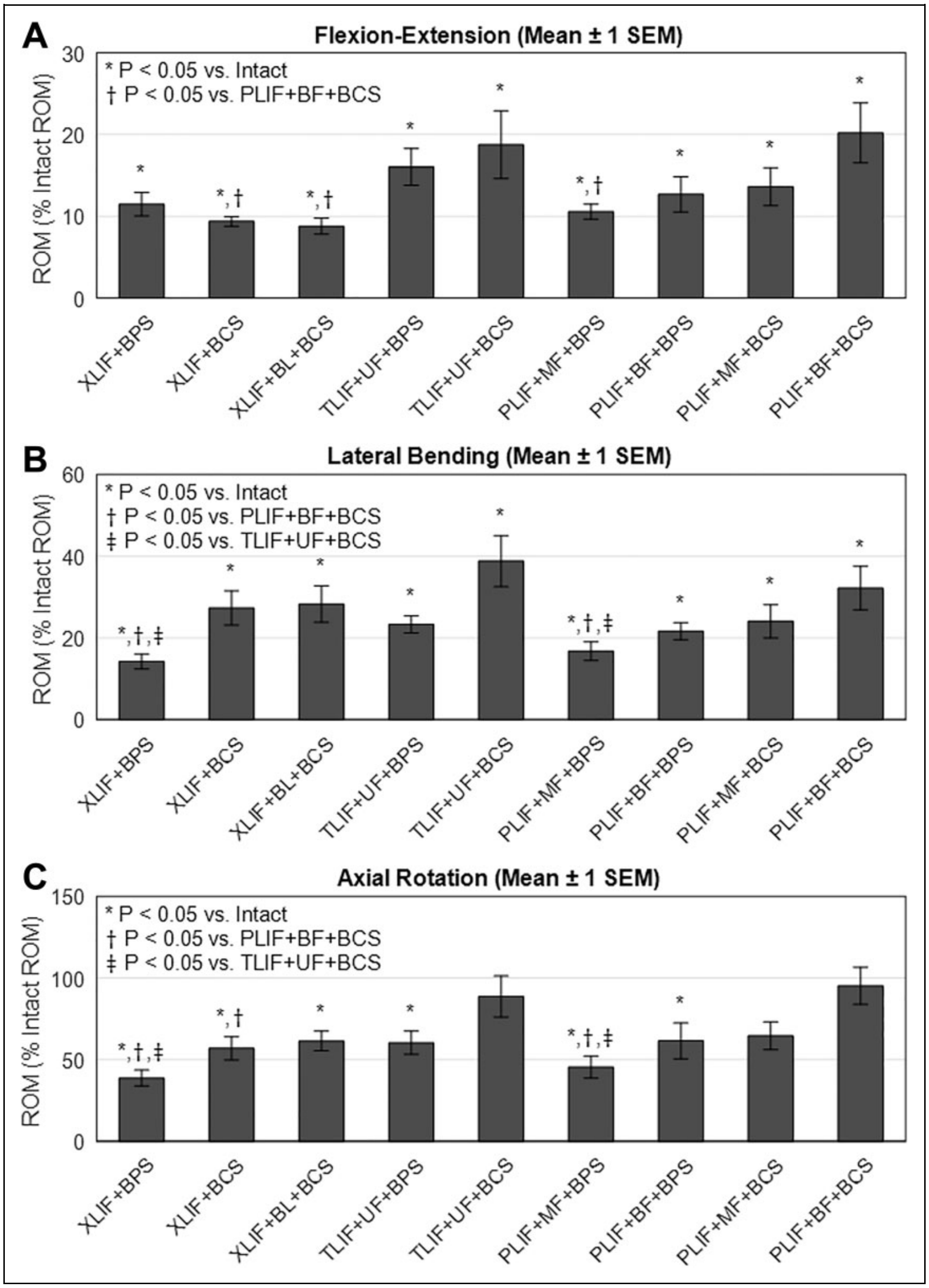

Figure 1. Mean normalized range of motion (% intact ROM) for each test condition in: (A) flexion-extension, (B) lateral bending, and (C) axial rotation. Error bars indicate ± 1 standard error of the mean (SEM). Test condition abbreviations are provided in Table 1.

comparing those instrumented with pedicle screw as well as those with cortical screw, indicating that the underlying stability comes from retention of anatomical structures associated with the interbody technique.

The importance of the facet joints in stabilizing the spine was demonstrated in this study when comparing the 2 PLIF constructs, where the BF test condition allowed numerically greater ROM compared with the MF in all directions tested. The largest differences were seen in axial rotation; however, no statistically significant differences were identified for any test directions. Facet joints are known to limit axial rotation in particular, as demonstrated by biomechanical studies reporting increased axial rotation following complete facetectomy.[41-43] The BLs performed with the XLIF constructs instrumented with BCS were found to have negligible impact on construct ROM (less than 5% intact ROM difference) and can thus be performed without introducing instability. A similar result can be expected for XLIF constructs with BPS.

In this study, no statistically significant differences were detected between pedicle and cortical screw stabilization of the same interbody technique. There was a trend toward less ROM in flexion-extension with cortical screws supplementing XLIF and TLIF constructs, and greater ROM with cortical screws in lateral bending and axial rotation for all interbody constructs. Perez-Orribo et al[28] compared pedicle and cortical screw trajectories in TLIF and XLIF interbody applications. They also reported no significant differences between screw types when augmenting XLIF constructs, although they found similar trends to the current study with reduced motion with the cortical screws in flexion-extension and increased motion in lateral bending and axial rotation. Perez-Orribo et al[28] did detect a significantly reduced stiff zone with the TLIF construct and cortical screws compared with pedicle screw fixation in lateral bending. The clinical implication of ROM and stiffness differences between screw trajectories requires further evaluation.

Long-term results for interbody fusions supplemented with cortical screw fixation are lacking. Short-term follow-up TLIF and PLIF studies indicate comparable clinical and radiographic outcomes at approximately 1 year to comparable interbody techniques with pedicle screws.[15,17] Additionally, these studies reported shorter incision length, quicker operative duration, and less blood loss compared with pedicle screws. Some case studies have reported screw loosening and loss of reduction; however, the majority of these did not include interbody support, which is likely a contributing factor.[14,44,45] Previous cadaveric cyclic toggle loading and pullout studies have reported equivalent or improved fixation strength for cortical trajectory screws over pedicle screws,[20,22-24] although a recent study reported lower fixation strength with cortical screws.[19] No screw loosening was observed in the current biomechanical study.

This study has limitations in common with other cadaveric biomechanical investigations. Sample size in each group was limited to 8, based on availability, although multiple spinal levels were used in each specimen to increase the sample sizes. Additional samples may have allowed for detection of more statistical differences between test conditions; however, since statistical significance may not be associated with clinical significance, *P* values should be interpreted with caution. The loading used is simplified and excludes the effect of surrounding musculature and body weight; however, it is a repeatable and accepted method that is independent of specimen size. Another limitation of the study is that the MF PLIF condition retaining the majority of the facet joints would not be clinically feasible at the higher lumbar levels in most cases as the space would be insufficient to insert the 2 PLIF cages around the thecal sac. Despite this, we were able to evaluate the biomechanical stability of this condition, which should be applicable to the lower lumbar levels where the use of cortical screws is more prevalent. Strengths of the study included testing of 3 different interbody techniques under identical loading conditions.

Conclusion

Supplemental fixation of single-level TLIF, PLIF, or XLIF constructs with either pedicle or cortical screws provided significant increases in immediate postoperative stability in flexion-extension and lateral bending compared with the intact condition. In axial rotation, most conditions were also more rigid than intact. For the same interbody and iatrogenic destabilization procedure, cortical trajectory screws typically allowed greater lateral bending and axial rotation ROM than pedicle trajectory screws, although not statistically different. For the same screw trajectory, iatrogenic destabilization was the primary ROM contributor with XLIF constructs being most rigid, followed by PLIF with facet joints mostly retained. TLIF with UF and PLIF with BF were least stable. Further investigation is warranted to understand the clinical implications of differences between constructs.

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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: Dr Nomoto has a teaching agreement with NuVasive, Inc. Dr Turner is an employee and stock holder of NuVasive. All other authors report no conflicts of interest concerning the materials or methods used in this study or the findings specified in this article. Materials for this study were provided by NuVasive and testing was performed at NuVasive facilities.

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References

1. Roy-Camille R, Saillant G, Mazel C. Plating of thoracic, thoracolumbar, and lumbar injuries with pedicle screw plates. *Orthop Clin North Am*. 1986;17:147-159.
2. Weinstein JN, Rydevik BL, Rauschning W. Anatomic and technical considerations of pedicle screw fixation. *Clin Orthop Relat Res*. 1992;(284):34-46.
3. Chen Z, Zhao J, Xu H, Liu A, Yuan J, Wang C. Technical factors related to the incidence of adjacent superior segment facet joint violation after transpedicular instrumentation in the lumbar spine. *Eur Spine J*. 2008;17:1476-1480. doi:10.1007/s00586-008-0776-9.
4. Lau D, Terman SW, Patel R, La MF, Park P. Incidence of and risk factors for superior facet violation in minimally invasive versus open pedicle screw placement during transforaminal lumbar interbody fusion: a comparative analysis. *J Neurosurg Spine*. 2013;18:356-361. doi:10.3171/2013.1.SPINE12882.
5. Moshirfar A, Jenis LG, Spector LR, et al. Computed tomography evaluation of superior-segment facet-joint violation after pedicle instrumentation of the lumbar spine with a midline surgical approach. *Spine (Phila Pa 1976)*. 2006;31:2624-2629. doi:10.1097/01.brs.0000240691.35707.e8.
6. Shah RR, Mohammed S, Saifuddin A, Taylor BA. Radiologic evaluation of adjacent superior segment facet joint violation following transpedicular instrumentation of the lumbar spine. *Spine*

(Phila Pa 1976). 2003;28:272-275. doi:10.1097/01.BRS.0000042361.93572.74.
7. Bogduk N, Wilson AS, Tynan W. The human lumbar dorsal rami. *J Anat*. 1982;134(pt 2):383-397.
8. Kim CW. Scientific basis of minimally invasive spine surgery: prevention of multifidus muscle injury during posterior lumbar surgery. *Spine (Phila Pa 1976)*. 2010;35(26 suppl):S281-S286. doi:10.1097/BRS.0b013e3182022d32.
9. Macintosh JE, Bogduk N. 1987 Volvo Award in Basic Science. The morphology of the lumbar erector spinae. *Spine (Phila Pa 1976)*. 1987;12:658-668.
10. Haig AJ, LeBreck DB, Powley SG. Paraspinal mapping. Quantified needle electromyography of the paraspinal muscles in persons without low back pain. *Spine (Phila Pa 1976)*. 1995; 20:715-721.
11. Sihvonen T, Herno A, Paljärvi L, Airaksinen O, Partanen J, Tapaninaho A. Local denervation atrophy of paraspinal muscles in postoperative failed back syndrome. *Spine (Phila Pa 1976)*. 1993;18:575-581.
12. Berjano P, Damilano M, Ismael M, Formica C, Garbosa D. Minimally invasive PLIF with divergent, cortical trajectory pedicle screws. *Eur Spine J*. 2015;24(suppl 5):654-655. doi:10.1007/s00586-015-3802-8.
13. Gautschi OP, Garbossa D, Tessitore E, et al. Maximal access surgery for posterior lumbar interbody fusion with divergent, cortical bone trajectory pedicle-screws: a good option for minimize spine access and maximize the field for nerve decompression. *J Neurosurg Sci*. 2017;61:335-341. doi:10.23736/S0390-5616.16.03230-6.
14. Glennie RA, Dea N, Kwon BK, Street JT. Early clinical results with cortically based pedicle screw trajectory for fusion of the degenerative lumbar spine. *J Clin Neurosci*. 2015;22:972-975. doi:10.1016/j.jocn.2015.01.010
15. Kasukawa Y, Miyakoshi N, Hongo M, Ishikawa Y, Kudo D, Shimada Y. Short-term results of transforaminal lumbar interbody fusion using pedicle screw with cortical bone trajectory compared with conventional trajectory. *Asian Spine J*. 2015;9:440-448. doi:10.4184/asj.2015.9.3.440.
16. Khanna N, Deol G, Poulter G, Ahuja A. Medialized, muscle-splitting approach for posterior lumbar interbody fusion: technique and multicenter perioperative results. *Spine (Phila Pa 1976)*. 2016;41(suppl 8):S90-S96. doi:10.1097/BRS.0000000000001475.
17. Lee GW, Son JH, Ahn MW, Kim HJ, Yeom JS. The comparison of pedicle screw and cortical screw in posterior lumbar interbody fusion: a prospective randomized noninferiority trial. *Spine J*. 2015;15:1519-1526. doi:10.1016/j.spinee.2015.02.038.
18. Mizuno M, Kuraishi K, Umeda Y, Sano T, Tsuji M, Suzuki H. Midline lumbar fusion with cortical bone trajectory screw. *Neurol Med Chir (Tokyo)*. 2014;54:716-721.
19. Akpolat YT, Inceoğlu S, Kinne N, Hunt D, Cheng WK. Fatigue performance of cortical bone trajectory screw compared with standard trajectory pedicle screw. *Spine (Phila Pa 1976)*. 2016; 41:E335-E341. doi:10.1097/BRS.0000000000001233.
20. Baluch DA, Patel AA, Lullo B, et al. Effect of physiological loads on cortical and traditional pedicle screw fixation. *Spine (Phila Pa 1976)*. 2014;39:E1297-E1302. doi:10.1097/BRS.0000000000000553.
21. Matsukawa K, Yato Y, Imabayashi H, Hosogane N, Asazuma T, Nemoto K. Biomechanical evaluation of the fixation strength of lumbar pedicle screws using cortical bone trajectory: a finite element study. *J Neurosurg Spine*. 2015;23:471-478. doi:10.3171/2015.1.SPINE141103.
22. Santoni BG, Hynes RA, McGilvray KC, et al. Cortical bone trajectory for lumbar pedicle screws. *Spine J*. 2009;9:366-373. doi:10.1016/j.spinee.2008.07.008.
23. Ueno M, Sakai R, Tanaka K, et al. Should we use cortical bone screws for cortical bone trajectory? *J Neurosurg Spine*. 2015;22:416-421. doi:10.3171/2014.9.SPINE1484.
24. Wray S, Mimran R, Vadapalli S, Shetye SS, McGilvray KC, Puttlitz CM. Pedicle screw placement in the lumbar spine: effect of trajectory and screw design on acute biomechanical purchase. *J Neurosurg Spine*. 2015;22:503-510. doi:10.3171/2014.10.SPINE14205.
25. Matsukawa K, Taguchi E, Yato Y, et al. Evaluation of the fixation strength of pedicle screws using cortical bone trajectory: what is the ideal trajectory for optimal fixation? *Spine (Phila Pa 1976)*. 2015;40:E873-E878. doi:10.1097/BRS.0000000000000983.
26. Matsukawa K, Yato Y, Kato T, Imabayashi H, Asazuma T, Nemoto K. In vivo analysis of insertional torque during pedicle screwing using cortical bone trajectory technique. *Spine (Phila Pa 1976)*. 2014;39:E240-E245. doi:10.1097/BRS.0000000000000116.
27. Calvert GC, Lawrence BD, Abtahi AM, Bachus KN, Brodke DS. Cortical screws used to rescue failed lumbar pedicle screw construct: a biomechanical analysis. *J Neurosurg Spine*. 2015;22:166-172. doi:10.3171/2014.10.SPINE14371.
28. Perez-Orribo L, Kalb S, Reyes PM, Chang SW, Crawford NR. Biomechanics of lumbar cortical screw-rod fixation versus pedicle screw-rod fixation with and without interbody support. *Spine (Phila Pa 1976)*. 2013;38:635-641. doi:10.1097/BRS.0b013e318279a95e.
29. Cheng WK, Inceoğlu S. Cortical and standard trajectory pedicle screw fixation techniques in stabilizing multisegment lumbar spine with low grade spondylolisthesis. *Int J Spine Surg*. 2015; 9:46. doi:10.14444/2046.
30. Beaubien BP, Derincek A, Lew WD, Wood KB. In vitro, biomechanical comparison of an anterior lumbar interbody fusion with an anteriorly placed, low-profile lumbar plate and posteriorly placed pedicle screws or translaminar screws. *Spine (Phila Pa 1976)*. 2005;30:1846-1851.
31. Kretzer RM, Molina C, Hu N, et al. A comparative biomechanical analysis of stand alone versus facet screw and pedicle screw augmented lateral interbody arthrodesis: an in vitro human cadaveric model. *Clin Spine Surg*. 2016;29:E336-E343. doi:10.1097/BSD.0b013e3182868ef9.
32. Laws CJ, Coughlin DG, Lotz JC, Serhan HA, Hu SS. Direct lateral approach to lumbar fusion is a biomechanically equivalent alternative to the anterior approach: an in vitro study. *Spine (Phila Pa 1976)*. 2012;37:819-825. doi:10.1097/BRS.0b013e31823551aa.

33. Ploumis A, Wu C, Mehbod A, et al. Revision of transforaminal lumbar interbody fusion using anterior lumbar interbody fusion: a biomechanical study in nonosteoporotic bone. *J Neurosurg Spine*. 2010;12:82-87. doi:10.3171/2009.7.SPINE0921.
34. Zheng X, Chaudhari R, Wu C, Mehbod AA, Erkan S, Transfeldt EE. Biomechanical evaluation of an expandable meshed bag augmented with pedicle or facet screws for percutaneous lumbar interbody fusion. *Spine J*. 2010;10:987-993. doi:10.1016/j.spinee.2010.08.016.
35. Dooley ZA, Turner AW, Cornwall GB. Multiaxial spine testing apparatus: system characterization by evaluation of analog and cadaveric lumbar spines. *Int J Exp Comput Biomech*. 2013;2:189-203. doi:10.1504/IJECB.2013.056544.
36. Panjabi MM. Biomechanical evaluation of spinal fixation devices: I. A conceptual framework. *Spine (Phila Pa 1976)*. 1988;13:1129-1134.
37. Wilke HJ, Wenger K, Claes L. Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. *Eur Spine J*. 1998;7:148-154.
38. Pimenta L, Turner AW, Dooley ZA, Parikh RD, Peterson MD. Biomechanics of lateral interbody spacers: going wider for going stiffer. *ScientificWorldJournal*. 2012;2012:381814. doi:10.1100/2012/381814.
39. Ames C P, Acosta FL Jr, Chi J, et al. Biomechanical comparison of posterior lumbar interbody fusion and transforaminal lumbar interbody fusion performed at 1 and 2 levels. *Spine (Phila Pa 1976)*. 2005;30:E562-E566.
40. Sim HB, Murovic JA, Cho BY, Lim TJ, Park J. Biomechanical comparison of single-level posterior versus transforaminal lumbar interbody fusions with bilateral pedicle screw fixation: segmental stability and the effects on adjacent motion segments. *J Neurosurg Spine*. 2010;12:700-708. doi:10.3171/2009.12.SPINE09123.
41. Abumi K, Panjabi MM, Kramer KM, Duranceau J, Oxland T, Crisco JJ. Biomechanical evaluation of lumbar spinal stability after graded facetectomies. *Spine (Phila Pa 1976)*. 1990;15:1142-1147.
42. Chutkan NB, Zhou H, Akins JP, Wenger KH. Effects of facetectomy and crosslink augmentation on motion segment flexibility in posterior lumbar interbody fusion. *Spine (Phila Pa 1976)*. 2008;33:E828-E835. doi:10.1097/BRS.0b013e318183bb6d.
43. Zander T, Rohlmann A, Klöckner C, Bergmann G. Influence of graded facetectomy and laminectomy on spinal biomechanics. *Eur Spine J*. 2003;12:427-434. doi:10.1007/s00586-003-0540-0.
44. Cheng WK, Akpolat YT, Inceoğlu S, Patel S, Danisa OA. Pars and pedicle fracture and screw loosening associated with cortical bone trajectory: a case series and proposed mechanism through a cadaveric study. *Spine J*. 2016;16:e59-e65. doi:10.1016/j.spinee.2015.09.046.
45. Patel SS, Cheng WK, Danisa OA. Early complications after instrumentation of the lumbar spine using cortical bone trajectory technique. *J Clin Neurosci*. 2016;24:63-67. doi:10.1016/j.jocn.2015.07.018.