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BIOMECHANICS

Spinolaminar locking plates improve fixation strength compared to pedicle screws: a biomechanical analysis

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Abstract

Introduction Pedicle screw loosening is a significant complication of posterior spinal fixation, particularly among osteoporotic patients and in deformity constructs. In orthopedic trauma surgery, locking plates and screws have revolutionized the fixation of osteoporotic fractures. We have combined the traumatology principle of fixed-angle locking plate fixation with the spine principles of segmental instrumentation.

Methods A novel spinolaminar locking plate was designed based on morphometric studies of human thoracolumbar vertebrae. The plates were fixed to cadaveric human lumbar spines and connected to form 1-level L1–L2 or L4–L5 constructs and compared to similar pedicle screw constructs. Pure moment testing was performed to assess range of motion before and after 30,000 cycles of cyclic fatigue. Post-fatigue fixture pullout strength was assessed by applying a continuous axial tensile force oriented to the principal axis of the pedicle until pullout was observed.

Results Spinolaminar plate fixation resulted in superior pullout strength compared to pedicle screws (1,065 ± 400N vs. 714 ± 284N, $p = 0.028$). Spinolaminar plates performed equivalently to pedicle screws in range of motion reduction during flexion/extension and axial rotation. Pedicle screws outperformed the spinolaminar plates in lateral bending. Finally, no spinolaminar constructs failed during cyclic fatigue testing, whereas one pedicle screw construct did.

Conclusions The spinolaminar locking plate maintained adequate fixation post-fatigue, particularly in flexion/extension and axial rotation compared to pedicle screws. Moreover, spinolaminar plates were superior to pedicle screw fixation with respect to cyclic fatiguing and pullout strength. The spinolaminar plates offer a viable option for posterior lumbar instrumentation in the adult spine.

Keywords Lumbar · Instrumentation · Pedicle screw · Spinolaminar plate · Biomechanics · Pullout

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Introduction

Recent studies have demonstrated increasing rates of lumbar fusion among patients ≥ 65 years, many of whom have osteoporosis [1–3]. While pedicle screws are the current gold standard for thoracolumbar instrumentation, the fixation strength depends on the structural integrity of the bone. Biomechanical studies have demonstrated decreased pullout strength and higher rates of pedicle fracture in osteoporotic bone [4, 5]. Moreover, traditional pedicle screw trajectories rely on the cancellous bone of the vertebral body—an area more affected by osteoporosis compared to cortical bone [6, 7].

Bone anchors in the osteoporotic appendicular skeleton are also prone to acute and delayed failures [5, 8, 9]. In orthopedic trauma, locking plates, which utilize the locking

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of individual screws into threaded holes of pre-contoured (anatomic) plates, have revolutionized the fixation of osteoporotic fractures [10–13]. These plates, which can accept cortical or locking screws, facilitate the distribution and dissipation of stresses and create fixed-angle constructs that are not dependent on the screw–bone interface, which are ideal for use in osteoporotic bone (Fig. 1). Furthermore, locking screw fixation does not rely on bicortical screw purchase, which offers an advantage in the spine when working in close proximity to the great vessels and neural structures. Additionally, they do not require perfect apposition of the plate to bone, which may be challenging in arthritic or deformed spines.

Locking plates are currently used in spinal procedures as an adjunct to interbody devices, or directly integrated into them. In anterior cervical decompression and fusion procedures, anterior plate constructs (APC) were used to stabilize and prevent interbody device extrusion. Locking stand-alone cages were developed to mitigate complications associated with APCs, such as postoperative dysphagia due to plate prominence, neurovascular injuries due to cage migration, and adjacent level ossification. Augmenting interbody devices with locking plates can increase the rigidity of the construct, shorten the length of plate and eliminate the requirement for additional posterior fixation [14–16].

We introduced an alternative form of posterior instrumentation that merges locking plate fixation, fixed-angle constructs, and segmental spine fixation. This novel "spinolaminar locking plate" relies on short, multidirectional locking screws inserted into the posterior spinal elements, which have been shown to be the densest regions of the vertebra [17]. A polyaxial head was then integrated into the plate to allow for easy connectivity of multiple anchors with rods. The purpose of this study was to measure the biomechanical strength of a novel spinolaminar cortical locking plate fixation as compared to traditional pedicle screws.

Fig. 1 A locking compression plate and locking screw used for open reduction and internal fixation in the appendicular skeleton

Methods

A pre-contoured 3.5 mm titanium locking plate with a polyaxial saddle was designed based on morphometric analyses of human thoracolumbar spines (Fig. 2A–C). The plates were designed for both sides of the spinal column and incorporated threaded holes for locking screw placement. In vitro biomechanical study using human cadaveric thoracolumbar spines was performed to compare spinolaminar plate fixation to pedicle screws.

All biomechanical tests were performed using a servohydraulic test frame (Instron 8521, Illinois Tool Works, Norwood, MA) with a uniaxial load cell mounted to an actuator head. A summary of the biomechanical testing protocol is depicted in Fig. 3.

Specimen preparation

In total, 6 cadaveric spines were utilized. The average age of the donors was 67 years (range 60–77 years) and consisted of 3 female and 3 male specimens. Each cadaveric spine was separated to create T12–L2 and L3–L5 segments, yielding 12 specimens. The upper and lower vertebral levels of each segment were potted in resin and augmented with Kirschner wires. Each segment from a single donor was randomly assigned using a randomized sequence allocation process to be instrumented with either spinolaminar plates or pedicle screws to form L1–L2 or L4–L5 single-level constructs with rods. In total, 3 L1–L2 spinolaminar, 3 L4–L5 spinolaminar, 3 L1–L2 pedicle screw, and 3 L4–L5 pedicle screw constructs were prepared. Pre-testing computerized tomography (CT) scans was performed on each specimen to assess bone mineral density (BMD) by measuring Hounsfield units (HU) on a single axial slice of the cancellous region of the vertebral body at L1, L2, L4, and L5 [18]. There were no significant differences in BMD between instrumentation groups (Table 1).

Pedicle screw fixation group

6.5 × 45 mm polyaxial pedicle screws (CD Horizon, Medtronic, Memphis TN) were used in the pedicle screw fixation group. 6.5 mm pedicle screws were chosen such that they would achieve at least 80% fill of the mean inner cortical pedicle width in all specimens (mean inner

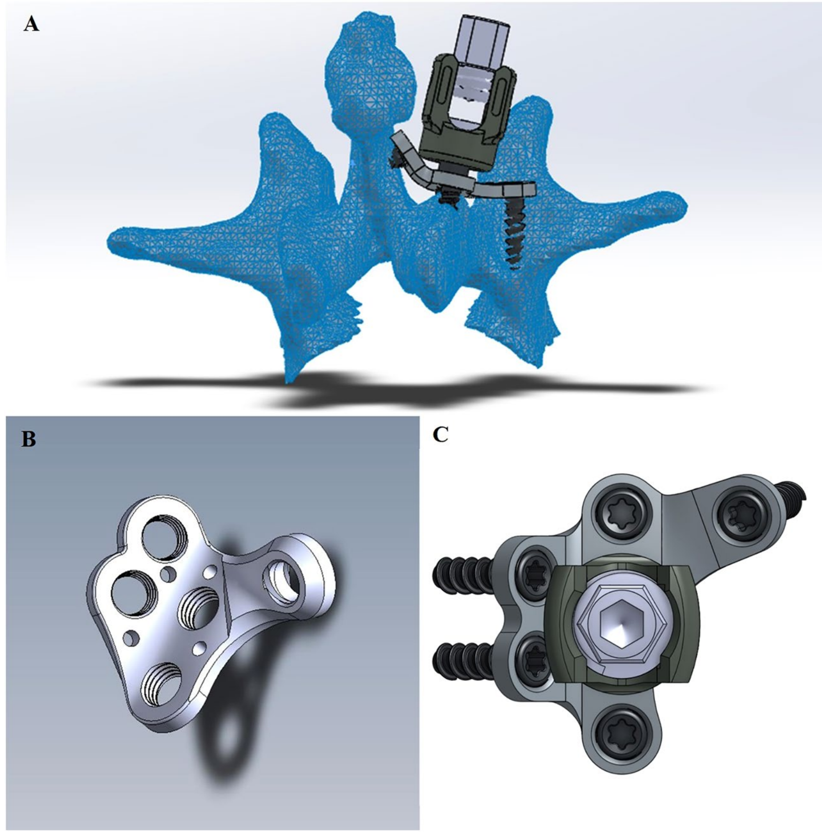

Fig. 2 **A-C**: Axial 3D reconstructions of the spinolaminar plate depicting: **A** the anatomic placement on the lamina **B**. Spinolaminar plate without screws and **C** the combination of locking screws and a polyaxial head and set screw

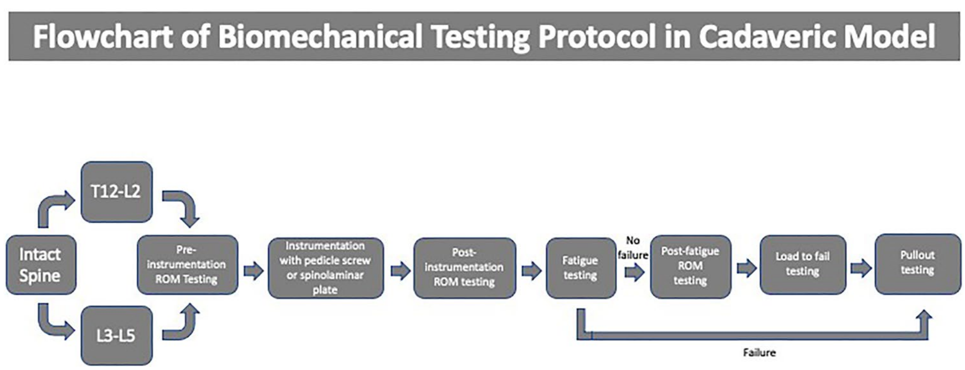

Fig. 3 Flowchart of biomechanical testing protocol in the cadaveric spine model

Table 1 Comparison of bone mineral density measured in Hounsfield Units (HU) between the spinolaminar plate and pedicle screw constructs

Group	Spinolaminar plate		Pedicle screw		*p-value*
	Mean HUs	SD	Mean HUs	SD	
All constructs	91.5	107.2	101.1	50.4	0.783
L1–L2	45.7	134.6	124.1	45.6	0.207
L4–L5	137.3	46.1	77.9	47.4	0.053

Analyses were performed for all constructs as well as L1–L2 and L4–L5 independently

cortical pedicle width: 7.6, range 2.6–14.6 mm). All constructs were prepared by a board-certified fellowship-trained spine surgeon. Anatomic freehand technique with fluoroscopic confirmation was used for instrumentation. The pedicles were cannulated using a Lenke pedicle probe and undertapped by 1 mm. The constructs were connected using 5 mm pre-contoured titanium rods and setscrews (Fig. 4A–C).

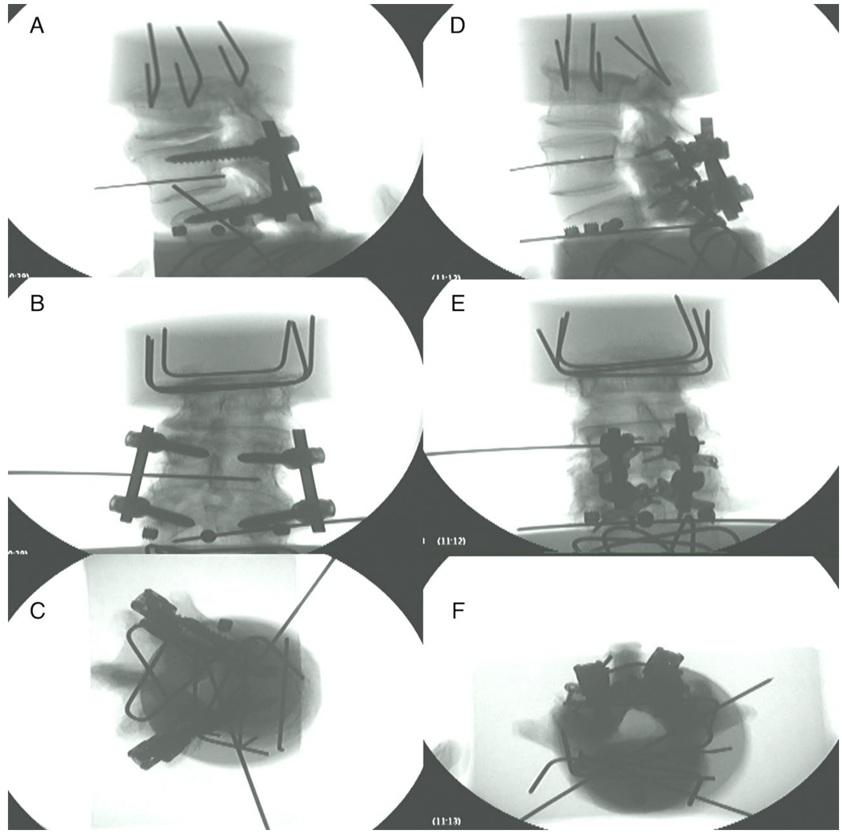

Fig. 4 Lateral, anterior–posterior, and axial radiographic images of an L1–L2 single-level posterior fusion construct using pedicle screw fixation (**A–C**) and an L4–L5 single-level posterior fusion construct using spinolaminar locking plate fixation (**D–F**)

Spinolaminar locking plate group

After positioning of the spinolaminar plates on the laminae, a total of 3–4 3.5 × 10-16 mm locking screws were inserted into the laminae, inferior articular processes, and spinolaminar junction. Threaded drill guides were used to guide the drilling of 2.35 mm pilot holes. A polyaxial locking screw connected to a polyaxial tulip head was then locked to the plate. The plates were connected using 5 mm pre-contoured titanium rods and setscrews. Positioning and trajectory of the locking screws were confirmed by fluoroscopy (Insight Fluoroscan Mini C-Arm, Hologic, Marlborough, MA) (Fig. 4D–F).

Range of motion testing

Range of motion (ROM) was tested for each spine segment in flexion–extension, axial rotation, and lateral bending moments using a previously described pure moment testing protocol [19]. Rigid body markers were placed in the upper (UIV) and lower instrumented vertebrae (LIV) and a 3D camera (Optotrak 3D Investigator, Northern Digital Inc, Waterloo, Ontario) was used to measure the relative motion between the L1 and L2 or L4 and L5 segments. (Fig. 5) ROM was recorded for each moment in 1.5Nm increments up to 7.5Nm. ROM testing was performed for each specimen prior to instrumentation ("pre-instrumentation"), after instrumentation ("post-instrumentation"), and following cyclic fatigue ("post-fatigue").

Cyclic fatigue testing

Fatigue testing was performed to assess construct failure or loss of fixation. In total, 30,000 cycles of combined flexion–compression–anterior shear at 17Nm–400N–200N, respectively, were applied to each specimen [20]. Evidence of construct failure was assessed every 5,000 cycles using videofluoroscopy (Fig. 6).

Load-to-failure testing

Maximum construct failure strength was assessed under a continuous combined flexion–compression–anterior shear moment of force angulation and moment arm at a rate of 1 mm/second until failure was observed. Videofluoroscopy was utilized throughout each test to observe the mechanism of failure (Fig. 6).

Pullout testing

Following load-to-failure testing, the UIV was dissected from each segment and repotted in plastic, keeping its

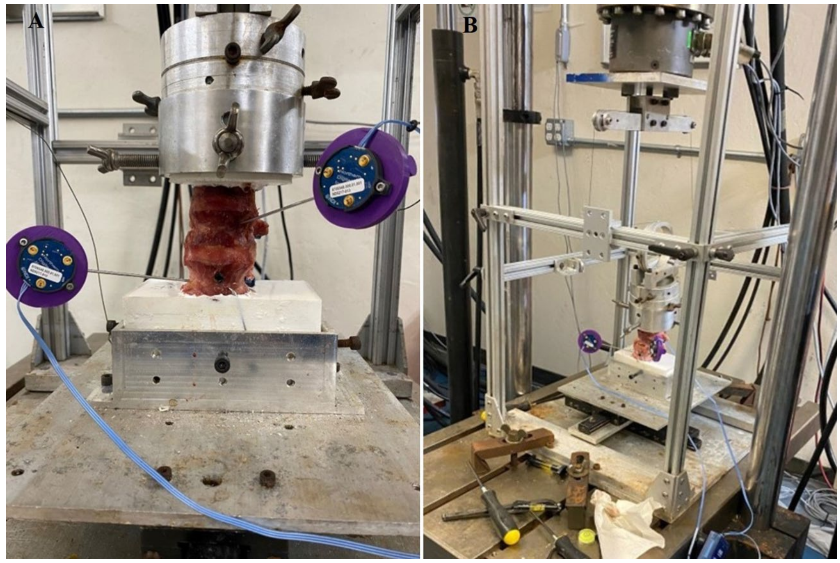

Fig. 5 Testing frame (Instron 8521, Illinois Tool Works, Norwood, MA) and 3D tracking markers (Optotrak 3D Investigator, Northern Digital Inc, Waterloo, Ontario) inserted at upper and lower instrumented vertebrae used to perform range of motion testing

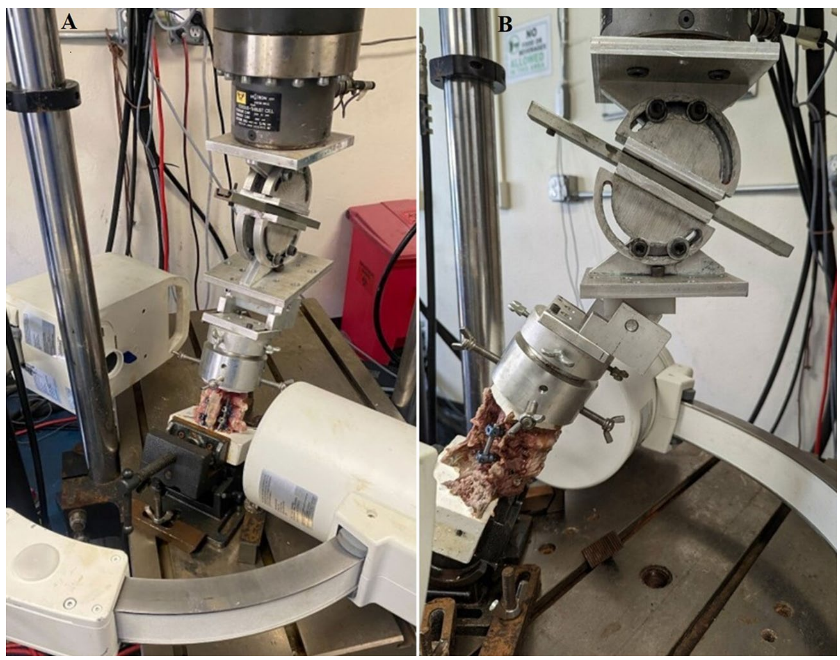

Fig. 6 Test frame (Instron 8521, Illinois Tool Works, Norwood, MA) used to perform cyclic fatigue and load-to-failure testing. The specimen is affixed to a fixture that applies a combined flexion–compression–anterior shear moment. Video fluoroscopy (Insight Fluoroscan Mini C-Arm, Hologic, Marlborough, MA) was performed during testing to identify the failure mechanism

respective instrumentation intact. A pure axial tensile load was applied to assess pullout strength. Each construct was subjected to a continuous vertical load oriented along the principal axis of the pedicle at a rate of 5 mm/minute until pullout was observed. A video of each test was recorded to analyze the mechanism of failure (Fig. 7A–B).

Data analysis

The primary outcome in this study was a pullout energy of the spinolaminar plates compared to pedicle screws. Secondary outcomes included pullout strength, ROM reduction before and after cyclic fatigue, and load-to-failure.

Spinal fixation post-instrumentation and post-fatigue was measured as the percent reduction in ROM from pre-instrumentation values. Construct failure strength was quantified by its maximum failure strength, which was defined as the lowest point on the compressive force–displacement curve. Pullout strength was quantified by mean pullout strength and failure energy. The maximum pullout strength was defined as the highest point on the tensile force–displacement curve [21]. Failure energy was defined as the area under the force–displacement curve prior to failure [22].

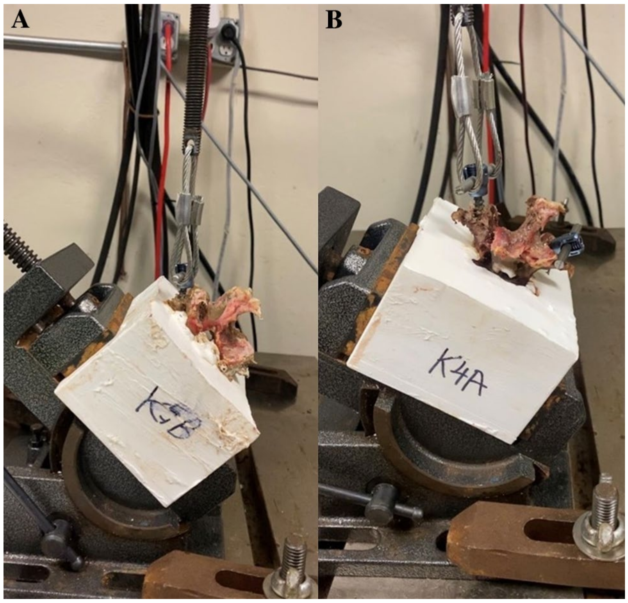

Fig. 7 Pullout testing fixtures used to perform pullout testing of the **A**. pedicle screw and **B** spinolaminar plate. The 5 mm/min continuous tensile force is applied along the principle axis of the pedicle screw and spinolaminar plate, respectively

Table 2 Table of pullout strength and pullout energy comparison between spinolaminar plate and pedicle screw

	Spinolaminar plate		Pedicle screw		*p* value
	n	Mean (SD)	*n*	Mean (SD)	
All constructs					
Pullout strength (*N*)	11	1065 (400)	12	714 (284)	0.028
Pullout energy (Nmm)	11	3937 (2412)	11	1668 (741)	0.007
L1–L2 constructs					
Pullout strength (*N*)	5	724 (35)	6	674 (143)	0.466
Pullout energy (Nmm)	5	2309 (791)	5	1801 (869)	0.362
L4–L5 constructs					
Pullout strength (*N*)	6	1354 (133)	6	801 (353)	0.018
Pullout energy (Nmm)	6	5294 (2,504)	6	1557 (680)	0.005
Failure by pullout constructs					
Pullout strength (*N*)	3	1169 (349)	11	723 (269)	0.037
Pullout energy (Nmm)	3	3378 (921)	11	1668 (741)	0.005

"*n*'' is the number of pullout tests performed under each condition

Descriptive statistics were used to summarize ROM, load-to-failure, and pullout data. A sample size calculation for the primary outcome was performed for equal variance unpaired *t* tests with 80% expected power, significance level of 5%, and large effect size (>0.80). In total, 5 specimens were required for this study. Normal distribution of the data for all endpoints was confirmed using Kolmogorov–Smirnov tests. *F* tests were used for equal variance data confirmation. Equal variance two-tailed unpaired *t* tests were used to assess for differences in all endpoints between the spinolaminar plate and pedicle screw groups. Statistical significance was defined as $p<0.050$. All statistical analyses were performed on STATA software (version 16.1; StataCorp LLC, College Station, TX).

Results

Pullout strength

The mean pullout energy ($3,937 \pm 2,412$ Nmm vs. $1,668 \pm 741$ Nmm, $p=0.007$) and strength ($1,065 \pm 400$ N vs. 714 ± 284 N, $p=0.028$) of the spinolaminar constructs were significantly greater than those of the pedicle screws. Similarly, mean pullout energy and strength were significantly increased in the spinolaminar plate group when the L4–L5 constructs were assessed independently ($p<0.050$). There were no differences in pullout strength in the L1–L2 constructs. Four spinolaminar plates failed by separation of the tulip from the central locking hole. Four spinolaminar and 2 pedicle screws failed by fracture of vertebral elements (Supplementary videos 1 and 2). In these tests, the plates and screws remained fixed (Table 2). The BMD of the UIV used to perform pullout testing (L1 and L4) were similar between the spinolaminar and pedicle screw cohorts (88.9 ± 30.7 HU vs. 86.4 ± 15.9 HU, $p=0.940$).

When accounting for pullout tests that resulted in complete construct pullout without vertebral damage or instrumentation damage, the spinolaminar plate constructs had significantly increased pullout energy ($3,378 \pm 921$ Nmm vs. $1,668 \pm 741$ Nmm, $p=0.005$) and strength compared to the pedicle screws (Table 2).

Range of motion

The mean pre-instrumentation ROM was not significantly different between the spinolaminar plate and pedicle screw groups in flexion/extension, axial rotation, and lateral bending ($p>0.05$). Instrumentation with plates or screws resulted in significantly reduced ROM in flexion/extension and lateral bending compared to pre-instrumentation values ($p<0.050$). Axial rotation was not significantly reduced. Post-fatigue, ROM did not increase significantly in any plane of motion compared to post-instrumentation values for either the plate or pedicle group ($p>0.05$) (Fig. 8).

When comparing the spinolaminar plates to pedicle screws, pedicle screws were observed to have greater ROM reduction in lateral bending post-instrumentation

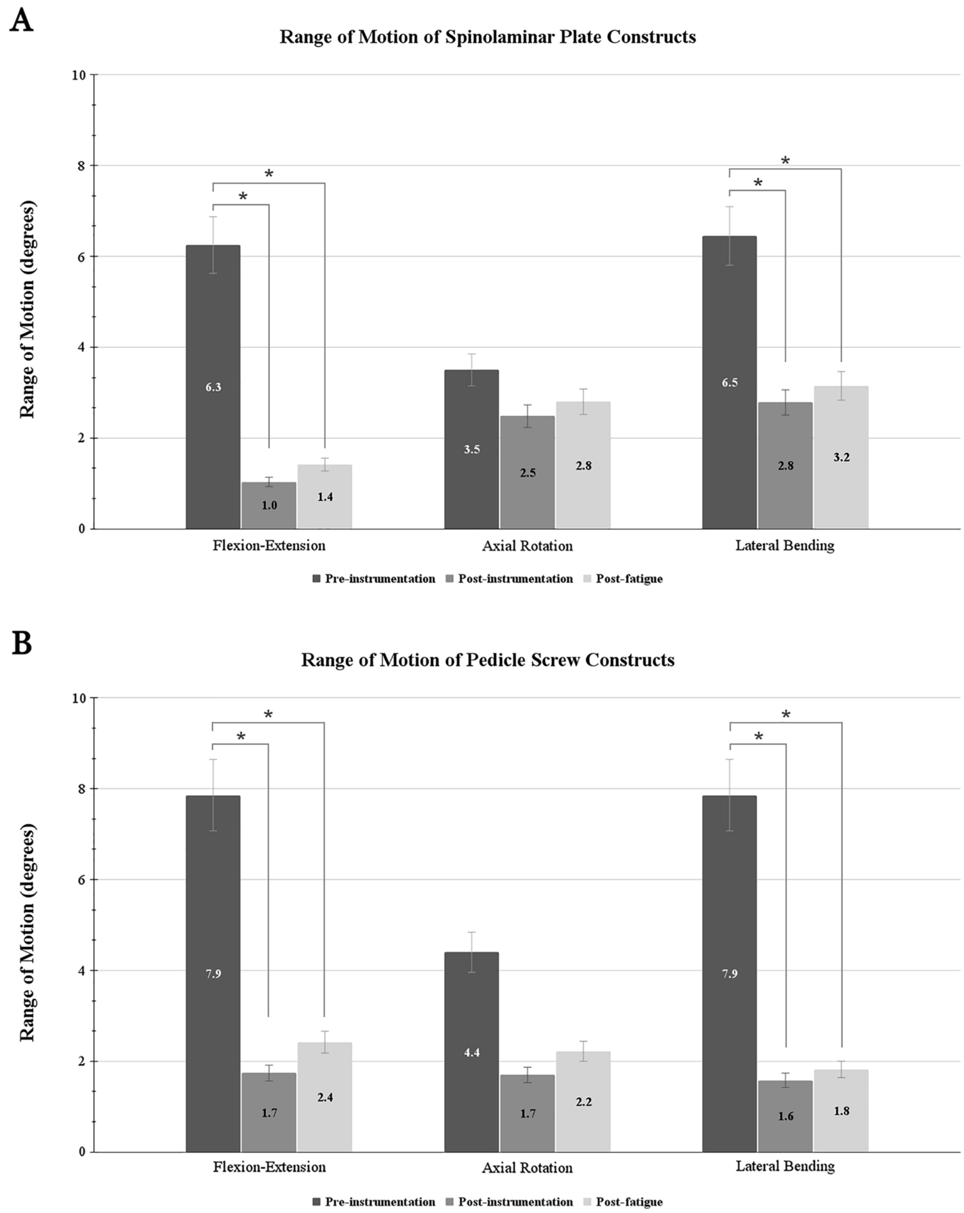

Fig. 8 Mean range of motion results for spinolaminar plates (**A**) and pedicle screws (**B**) prior to instrumentation, after instrumentation, and after fatigue testing in flexion/extension, axial rotation, and lateral bending. Data from one pedicle screw specimen was removed from this figure since post-fatigue range of motion could be performed due to specimen failure. The asterisks represent statistical significance

and post-fatigue relative to pre-instrumentation values. There were no differences in ROM reduction in flexion/extension and axial rotation (Fig. 9).

Fatigue

All specimens, except one, completed 30,000 cycles of fatigue without observable failure. One specimen (Specimen F: pedicle screw) failed due to specimen fracture during fatigue testing at < 5000 cycles. A second specimen (Specimen D: pedicle screw) failed after 30,000 cycles of fatigue by L2 screw toggling. No spinolaminar constructs failed during fatigue testing.

Load-to-failure

The mean load-to-fail strength of the spinolaminar constructs was 2236 ± 1174 N, while the mean load-to-failure strength of the pedicle screw constructs was 1968 ± 480 N ($p = 0.619$) (Fig. 10). There were no significant differences in load-to-failure strength between the plates and screws when L1–L2 and L4–L5 constructs were subanalyzed ($p > 0.050$). Failure for all specimens (both spinolaminar and pedicle screw) was due to superior endplate fracture of the UIV while the instrumentation remained fixed.

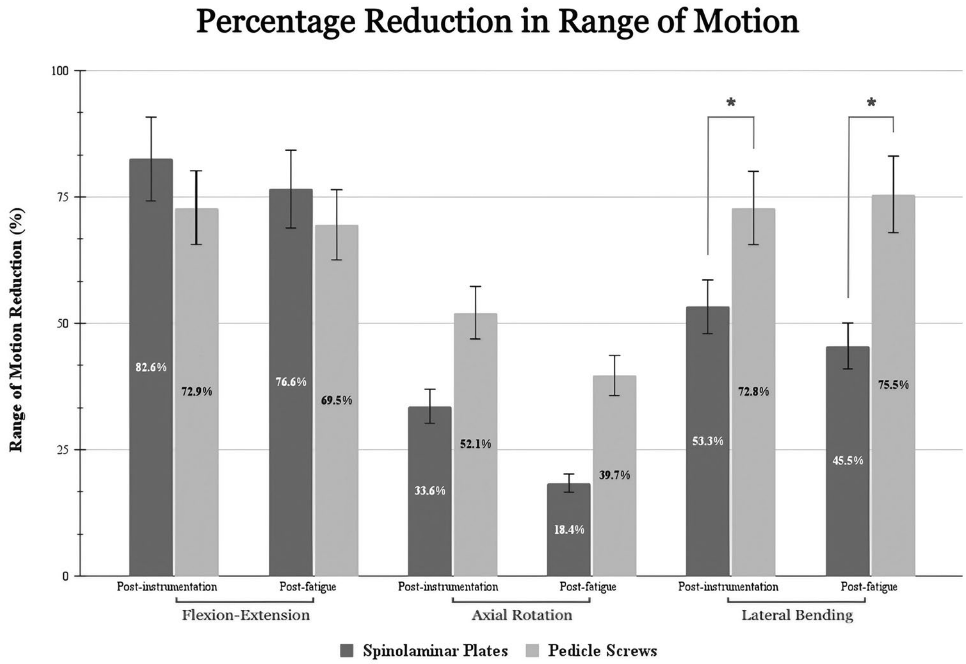

Fig. 9 Percent reduction of range of motion data after instrumentation and after fatigue testing relative to pre-instrumentation values for the spinolaminar plates compared to pedicle screws. The asterisks represent statistical significance

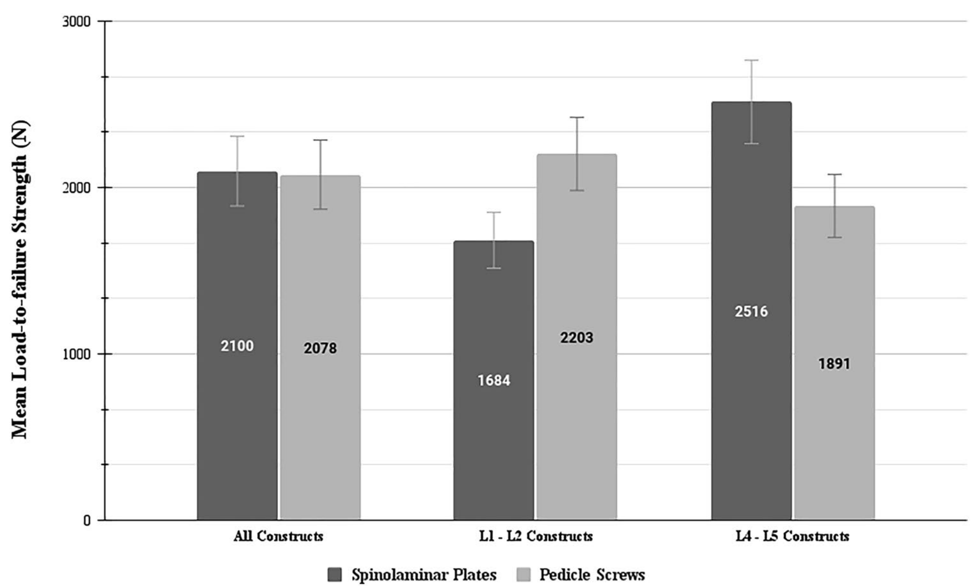

Fig. 10 Mean (with standard deviation) load-to-failure of the spinolaminar and pedicle screw groups for all constructs assessed in aggregate and L1–L2 and L4–L5 constructs assessed independently

Discussion

Achieving stable posterior spinal fixation in osteoporotic patients remains a challenge. Innovations in pedicle screw threading, core geometry, trajectory, expandability, and fenestration have been utilized to increase fixation strength [9]. Chen et al. compared the pullout strength of standard pedicle screws and expanding screws both with and without cement augmentation in an artificial osteoporotic bone model [22]. Standard pedicle screws alone had the lowest pullout strength, while expanding screws alone had similar pullout strength to pedicle screws with cement augmentation [22]. A disadvantage of cement augmentation is the risk of extravasation, pulmonary complications, embolization, and challenging revision [23]. Biomechanical studies have also demonstrated increased pullout strength and fatigue resistance of cortical bone trajectory (CBT) pedicle screws in osteoporotic and non-osteoporotic bone [7, 24, 25]. Despite the development of these techniques, a robust fixation remains a challenge in severely osteoporotic patients, and failure rates are relatively high especially at the ends of long fusion constructs.

Spinolaminar plate fixation may offer an alternative to pedicle screws and demonstrated an increased pullout energy strength in the present study. Of note, the majority of pullout tests with the spinolaminar constructs resulted in either vertebral fracture or plate/ polyaxial head separation without pullout of the plate itself. In 4 of the 12 spinolaminar pullout tests, the mechanism of failure was damage to the screw threads on the plate designated for the central polyaxial locking screw, or separation of the tulip from the polyaxial locking screw. Nevertheless, the mean pullout strength was significantly increased compared to pedicle screws. This finding is consistent with the spinolaminar plate's distribution of pullout forces over a larger area compared to pedicle screws. The spinolaminar plate also utilizes a greater screw thread surface area and a divergent configuration that may provide greater resistance to rotational, translational, and tensile forces [26]. Furthermore, Hohn et al. demonstrated a higher BMD in the inferior articular processes and laminae [7]. Thus, spinolaminar locking plates take advantage of multiple points of fixation in denser regions of the vertebrae compared to pedicle screws.

Both the spinolaminar plates and pedicle screws significantly reduced the ROM compared to pre-instrumentation values in flexion/extension and lateral bending. The spinolaminar plate constructs performed similarly to the pedicle screws in limiting the ROM in flexion/extension and axial rotation, but were inferior with regard to lateral bending. These findings may be explained by a design difference of the tulip-screw interface between the locking screw and pedicle screw tulips. In the spinolaminar plate constructs, tightening of the rod with a setscrew did not completely lock the tulip in place, which prevented the construct from achieving complete rigidity. This may explain the differences in ROM between the two groups, which may be resolved in future design iterations. Otherwise, the spinolaminar plates performed similarly to the pedicle screws to limit ROM, supporting its efficacy for use during posterior spinal instrumentation.

Spinolaminar plate instrumentation may also play a role in spinal tumor surgery. Pedicle screw pullout is the second most common cause of revision surgery for instrumentation failure in spinal tumor surgery [27]. In the elderly spine tumor patients with compromised BMD, the vertebrae may be further weakened by radiation and chemotherapy. A multilevel spine involvement combined with a decreased bone quality presents a major challenge for spinal fixation. Moreover, tumors frequently affect the vertebral body, leaving the posterior elements intact. Spinolaminar plate fixation, therefore, would be of potential benefit in these patients as it does not rely on vertebral body purchase. Additionally, spinolaminar locking plates, which allow multiple fixation points at an individual level, may reduce the lengths of a construct. Finally, the use of spinolaminar locking plate fixation can be a revision strategy for pedicle screw pullout/loosening, since transpedicular bone grafting options are limited.

The strengths of our study include testing spinolaminar locking plates in human cadaveric thoracolumbar spines, which closely replicates in vivo conditions. The use of the cadaveric bone models also allowed for a robust analysis of ROM before and after cyclic fatiguing, using a previously validated ROM testing protocol [19]. Our study involved the use of multiple testing modalities including range of motion, cyclic fatigue, load-to-failure, and pullout, which allowed the spinolaminar plates to be tested under multiple conditions. Our cadaveric specimens were similar to the patient population that would benefit from locking plate technology, including age ≥ 60 years old with age-related degenerative changes.

Our study is not without limitations. First, the cadaveric models cannot fully replicate an in vivo model, which may limit the applicability of this data to clinical conditions. However, the aim of this study was to provide a proof of concept of the spinolaminar plates, and a cadaveric study design would be the closest to in vivo conditions. Second, the tulip design used in the spinolaminar plates may have limited their performance compared to the pedicle screw group. However, despite these limitations, we demonstrated a similar performance with regards to ROM reduction and superior pullout strength. Future design iterations will aim to incorporate different plate sizes and shapes, test hybrid constructs combining plates and pedicle screws and optimize construct rigidity.

Conclusions

Spinolaminar locking plate fixation resulted in improved pullout strength and energy compared to pedicle screws. With regards to ROM reduction, spinolaminar plates were non-inferior to pedicle screws in flexion/extension and axial rotation. Locking plate fixation may be advantageous compared to pedicle screws in reducing rates of instrumentation failure among osteoporotic patients, as evidenced by fewer cases of failure during cyclic fatiguing. Future studies are needed to assess the performance of the plates in long constructs, younger bone, thoracic spine, and in hybrid constructs combined with pedicle screws. Furthermore, these positive findings warrant additional larger studies which utilize different pedicle screw designs (dual thread, fenestrated, HA-coated, cylindrical vs. conical shaft) and cement augmentation in the comparator groups. Nonetheless, spinolaminar locking plate fixation appears to be a viable posterior instrumentation technique.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43390-023-00716-8.

Author contributions DK: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. AP: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. VU: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. AS: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. AR: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. AD: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. NZ: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes. ORR: data collection, writing—original draft preparation, approval of final version of manuscript, agree to be accountable for the work. Meets 4 criteria: yes.

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Data availability The testing data presented in this study can be shared upon request.

Declarations

Conflict of interest ORR: Paid Consultant: Aurora Spine and Pain Care, PainTEQ, Osteo Centric Technologies, Facet Dynamics, Olympus Terumo Biomaterials. DGK: AO Foundation: Research Support; SI, Bone, Spineart: Paid consultant, Paid presenter or speaker; Spineart: IP Royalties. The remaining authors do not have any direct or indirect competing interests to disclose.

Ethical approval (IRB) This study was exempt from IRB approval as no live human subjects were used to conduct the study.

Informed consent Informed consent is not applicable to this study.

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