

Pedicle Screws Provide Superior Fatigue Resistance compared with lateral mass Screws in the subaxial cervical spine: A Paired Cadaveric Study

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Abstract

Purpose

To compare cervical pedicle screws (PS) and lateral mass screws (LMS) using a progressively increasing cyclic cranio-caudal toggle fatigue test that more closely reflects repetitive in vivo loading and gradual screw loosening than conventional axial pullout testing.

Methods

Ten human subaxial cervical vertebrae (C3–C7) from six donors were instrumented with contralateral PS and LMS. Screws underwent sinusoidal loading at 0.5 Hz, starting at 0–25 N and increasing by 0.1 N per cycle until 5-mm displacement. Primary outcomes were maximum fatigue load and cycles to failure; stiffness and exploratory vBMD associations were also assessed.

Results

PS achieved a significantly greater maximum fatigue load than LMS (252.4 ± 56.5 vs 166.4 ± 35.8 N; paired difference, 86.0 N; 95% CI, 64.4–107.6; $P < .001$) and endured more cycles to 5-mm displacement (2573 ± 479 vs 1636 ± 386 ; difference, 937; 95% CI, 719–1154; $P < .001$). Median initial stiffness was higher with PS (238.8 vs 139.7 N/mm; $P = .008$), as was end stiffness (50.2 ± 11.2 vs 33.0 ± 7.0 N/mm; $P < .001$), whereas relative stiffness loss did not differ ($P = .403$). All vertebral pairs favored PS for both primary outcomes.

Conclusion

Cervical pedicle screws provided substantially greater resistance to progressive cyclic loading than lateral mass screws. Fatigue-to-displacement testing captures progressive fixation loss under repetitive loading and may complement conventional axial pullout testing. When secure pedicle placement is feasible, pedicle fixation may offer a mechanical advantage in the subaxial cervical spine.

Introduction

Posterior screw fixation is established for traumatic, neoplastic, inflammatory, and degenerative disorders of the subaxial cervical spine. Lateral mass screws are widely used because they provide reliable posterior fixation [1], but purchase is confined to the posterior elements and may be limited when bone stock is compromised. Cervical pedicle screws traverse the pedicle into the vertebral body, providing a longer bone-screw interface and additional cortical fixation.

Previous biomechanical studies have demonstrated stronger anchorage of cervical PS than LMS, including greater axial pullout resistance, reduced loosening after cyclic loading, greater residual pullout strength, and superior construct stability [2–7]. Most direct comparisons, however, have relied on static or residual axial pullout after predefined cyclic loading. Axial extraction represents a simplified failure

mode, whereas clinical loosening develops progressively through repetitive loading, micromotion, and toggling. Progressive cyclic fatigue testing with a displacement-defined endpoint may therefore better characterize time-dependent fixation loss than conventional axial pullout testing [8–10].

In the subaxial cervical spine, Johnston et al. demonstrated less progressive loosening of PS during uniplanar cyclic loading, but testing ended after a predefined number of cycles and the terminal outcome remained axial pullout strength [3]. Direct paired data comparing PS and LMS under progressively increasing cyclic loading to a displacement-defined endpoint remain limited.

The aim was to compare the fatigue resistance of cervical PS and LMS in a paired human cadaveric model under progressively increasing cranio-caudal sinusoidal screw-head loading.

Materials and Methods

The alternative hypothesis was that cervical PS would withstand a higher maximum fatigue load, endure more cycles to 5-mm displacement, and maintain greater end stiffness than LMS; the null hypothesis was that no paired differences would occur in these outcomes.

Study Design and Specimen Selection

This experimental study used 10 isolated C3–C7 vertebrae from six donor spines with preserved osseous anatomy allowing paired PS and LMS instrumentation. Each vertebra served as its own control, with PS and LMS placed contralaterally. Side allocation and testing order were randomized for the first specimen and alternated thereafter, yielding five first tests per screw type.

Fresh-frozen specimens were obtained through the institutional body donation program. CT was performed before freezing to assess osseous integrity and BMD; specimens were stored below -20°C . Exclusion criteria were prior fracture, osteolytic or other destructive osseous changes, previous instrumentation, severe anatomical deformity, or major imaging artifacts. Specimens underwent a single freeze-thaw cycle and were thawed overnight at room temperature.

Bone Mineral Density Assessment

Noncontrast CT was performed using a Siemens SOMATOM Definition AS+ scanner (Siemens Healthineers, Erlangen, Germany) at 120 kVp with a 500-mm source field of view. Images were reconstructed using I30f/B30s filters with 1.0-mm slice thickness and 0.75–1.0-mm increment. Scanner calibration was performed asynchronously with a Mindways calibration phantom on the same scanner at 4–8-week intervals. Trabecular volumetric bone mineral density (vBMD), previously used to characterize bone quality in biomechanical fatigue testing of pedicle screw fixation [9], was quantified in mg/cm^3 using QCT Pro with the CliniQCT module (Mindways Software Inc., Austin, TX, USA). An elliptical region of interest was positioned centrally within the trabecular compartment approximately 1 mm inside the

cortical margin and visually inspected and adjusted when necessary to exclude cortical bone, endplate sclerosis, focal osseous lesions, or imaging artifacts.

Specimen Preparation and Instrumentation

After overnight thawing, soft tissues were removed while preserving structures required for instrumentation. During preparation and testing, specimens were moistened with Ringer solution, consistent with established biomechanical fatigue-testing protocols [7, 9].

Identical 3.5-mm polyaxial screws from the OASYS Occipito-Cervico-Thoracic System (Stryker, Kalamazoo, MI, USA) were used for both fixation techniques and inserted before potting. Screw length was selected from pre-test CT data and ranged from 12 to 16 mm for LMS and 26 to 34 mm for PS. PS were inserted along the anatomical pedicle axis and LMS according to the Magerl technique. Screw channels were drilled and circumferentially probed to confirm an intact osseous corridor. All screws were inserted unicortically without prior tapping by a single experienced spine surgeon under fluoroscopic guidance. Final position was confirmed in anteroposterior and lateral fluoroscopic projections (Fig. 1).

Specimen Potting and Mechanical Setup

After instrumentation, each vertebra was embedded in a custom-made spherical fixture using self-polymerizing acrylic resin (Vertex Castapress, Vertex-Dental B.V., Soesterberg, the Netherlands). The vertebral body was embedded anteriorly to the posterior vertebral wall, while the pedicles, lateral masses, posterior elements, screw heads, and adjacent screw portions remained unembedded and unconstrained.

Specimens were mounted in a 3-kN LTM3 T dynamic testing system (ZwickRoell GmbH & Co. KG, Ulm, Germany; system ID D0746937), with the tested screw head centered beneath the loading axis. A 3.5-mm rod in the loading adapter was seated in the polyaxial screw head and secured with an OASYS blocker tightened to 3 N·m using a calibrated torque wrench with counter-torque. The rotational axis passed through the screw-head center perpendicular to the screw trajectory. The joint allowed one degree of freedom while constraining the others, enabling reproducible cranio-caudal toggle loading without an additional moment at the screw head. The setup was adapted from established cyclic fatigue-testing protocols [9, 11–13] (Fig. 2).

Progressive Cyclic Fatigue Testing and Outcome Measures

Each screw underwent progressively increasing cranio-caudal toggle loading at 0.5 Hz, starting at 0–25 N, with target peak force increasing by 0.1 N per cycle. Because testing was force-controlled, maximum fatigue load was determined from recorded force. Crosshead displacement was recorded continuously,

and testing terminated automatically at 5-mm displacement [7, 9]. After failure of the first screw, the fixture was realigned and the contralateral screw tested identically.

Primary outcomes were maximum fatigue load and cycles to 5-mm displacement. Although related by the loading protocol, they were not interchangeable because maximum fatigue load was derived from recorded force. Secondary outcomes were initial stiffness, end stiffness, and relative stiffness loss. Stiffness was the slope of the linear loading portion of the force–displacement curve after excluding the first and last 10% of data points. Initial and end stiffness were calculated from the first and last complete cycles, respectively; relative stiffness loss was the percentage reduction between them.

Biomechanical data were acquired and processed using testXpert R software, version 6.0.3 (ZwickRoell GmbH & Co. KG, Ulm, Germany).

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, version 25.0 (IBM Corp., Armonk, NY, USA) at the vertebral-pair level. Continuous data are presented as mean $\pm$ standard deviation or median with interquartile range, as appropriate. Normality of paired differences was assessed using the Shapiro-Wilk test. Normally distributed paired outcomes were compared using paired t tests; initial stiffness was analyzed using the Wilcoxon signed-rank test. Mean paired differences are reported with 95% confidence intervals and Cohen d where applicable.

Exploratory linear regressions assessed whether vertebral BMD modified the paired screw effect (PS minus LMS). BMD was centered at the sample mean. Regression slopes, 95% confidence intervals, P values, and R^2 are reported; $P < .05$ was considered statistically significant. No adjustment for multiple testing was applied because of the exploratory design and small sample.

Results

Specimen Characteristics

All 10 vertebral pairs completed testing and were included in the analysis, comprising 20 screws (10 PS and 10 LMS). vBMD ranged from 82.1 to 267.3 mg/cm³.

Table 1
Specimen Characteristics

Characteristic	Value
Donor spines, n	6
Vertebral pairs, n	10
Screws tested, n	20 (10 PS; 10 LMS)
Levels	C3: 2; C4: 3; C5: 3; C6: 1; C7: 1
Age, mean $\pm$ SD (range), y	70.8 $\pm$ 9.3 (61–86)
Sex among donors	4 female; 2 male
Trabecular BMD, mean $\pm$ SD (range), mg/cm ³	197.8 $\pm$ 57.0 (82.1–267.3)

Maximum Fatigue Load and Cycles to Failure

Pedicle screws withstood a significantly higher maximum fatigue load than lateral mass screws (252.4 ± 56.5 vs 166.4 ± 35.8 N; mean paired difference, 86.0 N; 95% CI, 64.4–107.6 N; $P < .001$; Cohen $d = 2.85$), corresponding to a 51.7% higher maximum fatigue load. All 10 vertebral pairs favored pedicle screw fixation (Fig. 3).

Pedicle screws also endured significantly more loading cycles before reaching the 5-mm displacement threshold (2572.8 ± 478.8 vs 1636.0 ± 386.2 cycles; mean paired difference, 936.8 cycles; 95% CI, 719.4–1154.2; $P < .001$; Cohen $d = 3.08$), corresponding to a 57.3% increase. Again, all 10 vertebral pairs favored pedicle screw fixation. The paired biomechanical results are summarized in Table 2.

Table 2
Paired Biomechanical Comparison. Values are mean $\pm$ SD except initial stiffness, which is median (interquartile range). PS, pedicle screw; LMS, lateral mass screw.

Outcome	Pedicle screw	Lateral mass screw	Paired difference (95% CI)	P value	Effect size
Maximum fatigue load, N	252.4 ± 56.5	166.4 ± 35.8	86.0 (64.4 to 107.6)	$< .001$	$d = 2.85$
Cycles to 5-mm displacement	2572.8 ± 478.8	1636.0 ± 386.2	936.8 (719.4 to 1154.2)	$< .001$	$d = 3.08$
Initial stiffness, N/mm	238.8 (163.3–380.9)	139.7 (77.9–201.3)	Wilcoxon signed-rank	.008	—
End stiffness, N/mm	50.2 ± 11.2	33.0 ± 7.0	17.1 (12.9 to 21.4)	$< .001$	$d = 2.87$
Stiffness loss, %	74.7 ± 19.3	71.0 ± 15.1	3.6 (–5.7 to 13.0)	.403	$d = 0.28$

Stiffness

Initial stiffness was non-normally distributed. Median initial stiffness was 238.8 N/mm (interquartile range, 163.3–380.9) for pedicle screws and 139.7 N/mm (77.9–201.3) for lateral mass screws ($P = .008$). One markedly high pedicle-screw initial-stiffness value occurred in the specimen with the lowest vBMD.

End stiffness was significantly higher for pedicle screws than for lateral mass screws (50.2 ± 11.2 vs 33.0 ± 7.0 N/mm; mean paired difference, 17.1 N/mm; 95% CI, 12.9–21.4; $P < .001$; Cohen $d = 2.87$), corresponding to a 51.8% higher mean end stiffness. Relative stiffness loss did not differ significantly ($74.7\% \pm 19.3\%$ vs $71.0\% \pm 15.1\%$; mean paired difference, 3.6 percentage points; 95% CI, – 5.7 to 13.0; $P = .403$).

Exploratory BMD Analysis

BMD was significantly associated with the paired difference in initial stiffness. For each 10-mg/cm³ increase in BMD, the pedicle-screw advantage in initial stiffness decreased by 44.1 N/mm (slope, – 4.41 N/mm per mg/cm³; 95% CI, – 8.10 to – 0.71; $P = .025$; $R^2 = 0.486$). This association was strongly influenced by the low-BMD specimen with the largest initial-stiffness difference and should therefore be interpreted cautiously. No significant associations were observed for maximum fatigue load, cycles to 5-mm displacement, end stiffness, or relative stiffness loss (Table 3).

Cycles to 5-mm displacement increased numerically with increasing vBMD for both fixation techniques, but the associations were not statistically significant (PS, $P = .205$; LMS, $P = .557$; Fig. 4).**Fig. 4** Relationship between vertebral volumetric bone mineral density (vBMD) and cycles to 5-mm displacement for pedicle screws (PS) and lateral mass screws (LMS). Individual data points represent the 10 paired cervical vertebral specimens. Solid lines indicate the linear regression fits, with shaded areas representing the 95% confidence intervals. Horizontal dotted lines indicate the mean number of cycles to 5-mm displacement for PS (2572.8 cycles) and LMS (1636.0 cycles). No significant association between vBMD and cycles to 5-mm displacement was observed for either PS ($P = .205$) or LMS ($P = .557$).

Table 3. Exploratory Regression of Paired Screw Effect on Bone Mineral Density. The paired screw effect was defined as PS minus LMS. Negative values indicate that the PS advantage decreased with increasing BMD. Analyses are exploratory.

Outcome	Slope per 10 mg/cm ³ BMD (95% CI)	P value	R ²
Maximum fatigue load, N	3.28 (-0.11 to 6.67)	.056	0.384
Cycles to failure	22.5 (-16.9 to 61.9)	.224	0.178
Initial stiffness, N/mm	-44.1 (-81.0 to -7.1)	.025	0.486
End stiffness, N/mm	0.64 (-0.04 to 1.32)	.060	0.374
Stiffness loss, percentage points	-1.14 (-2.77 to 0.50)	.147	0.243

Discussion

The principal finding of this paired cadaveric study was that cervical pedicle screws provided substantially greater resistance to progressive cyclic loading than lateral mass screws. Pedicle screws sustained approximately 52% higher maximum fatigue loads, endured approximately 57% more cycles before 5-mm displacement, and retained approximately 52% greater stiffness at the end of testing. The direction of effect was consistent across every vertebral pair for maximum load, cycles to failure, and end stiffness.

These results are consistent with previous biomechanical comparisons. Jones et al. reported higher axial pullout resistance of cervical pedicle screws, Kothe et al. demonstrated superior primary and post-cyclic stability, and Ito et al. found greater residual pullout strength after cyclic loading [2, 4, 14]. Johnston et al. showed more rapid loosening and lower residual pullout strength of lateral mass screws during uniplanar fatigue loading [3]. The present study extends these observations by using progressively increasing cyclic loading to a displacement-defined failure endpoint rather than terminal axial pullout.

This distinction is important because pullout and fatigue tests assess different aspects of the bone-screw interface. Pullout testing measures extraction along the screw axis, whereas clinical loosening develops gradually through repetitive loading and toggling. Studies comparing both methods have shown that relative performance may differ and have questioned the direct clinical transferability of axial pullout results [9, 10, 15, 16]. The current protocol quantified load and cumulative cycles to progressive displacement-defined failure. Although simplified, this approach more closely reflects the time-dependent nature of screw loosening in vivo.

The longer pedicle-screw trajectory, cortical pedicle engagement, and vertebral-body purchase probably explain the observed advantage. Cortical purchase may contribute substantially to resistance against cyclic toggle loading; previous work has shown that, in bone of normal quality, pedicle screw anchorage is predominantly provided within the pedicle [17]. These features increase bone-screw contact across cortical and trabecular regions. Higher end stiffness indicates that this benefit persisted throughout cyclic loading, whereas similar proportional stiffness loss suggests substantial degradation of both screw types while pedicle screws maintained higher absolute stiffness.

The exploratory BMD analysis suggested that the initial-stiffness advantage of pedicle screws may be greater at lower BMD. This is biologically plausible because engagement of the pedicle cortex may partly compensate for reduced trabecular support. BMD is an established determinant of screw fixation and fatigue strength [9, 18]. However, this secondary finding was based on only 10 pairs, was dominated by one influential low-BMD observation, and should therefore be considered hypothesis-generating.

The biomechanical benefit of cervical pedicle screws must be balanced against the technical demands and potential neurovascular consequences of insertion. The cervical pedicle is narrow, its transverse angle varies by level, and cortical breach may endanger the vertebral artery, nerve root, or spinal cord.

Clinical series show that cervical pedicle screw fixation can be performed successfully with careful preoperative planning and fluoroscopic or navigated insertion, but complications remain possible [1, 19–21]. The present findings therefore support pedicle screw use when high fixation strength is required and a safe pedicle corridor can be established, rather than indiscriminate use in all patients.

A major strength was the paired design, which minimized interspecimen differences in anatomy and bone quality; balanced allocation and consistent effects across pairs further support the findings.

Limitations

Several limitations should be acknowledged. First, the isolated-vertebra model did not reproduce a multilevel cervical construct with adjacent segments, soft-tissue forces, or multidirectional loading. The cranio-caudal toggle protocol represents one mechanism of loosening but not the full complexity of in vivo loading. Second, crosshead displacement rather than local optical tracking was used and may include compliance of the testing frame, adapter, fixture, and potting material. The 5-mm threshold is an experimental failure criterion without clinical validation.

Third, the two screws within each vertebra were tested sequentially; despite balanced testing order, a carryover effect cannot be excluded. Fourth, the small sample included several vertebrae from the same donor spines, and vertebral-pair analysis may not fully account for within-donor dependence. Donor demographic data were incomplete, and the BMD range may not fully represent severely osteoporotic cervical bone. Fifth, screw length and trajectory necessarily differed between fixation techniques, preventing attribution of the observed advantage specifically to pedicle engagement, screw length, or vertebral-body purchase. Finally, the exploratory BMD analyses were based on 10 pairs and sensitive to one influential low-BMD observation and should therefore be regarded as exploratory. The study assessed immediate mechanical behavior only and did not evaluate clinical outcomes or biological healing, remodeling, or fusion.

Conclusions

Cervical pedicle screws demonstrated superior fatigue resistance compared with lateral mass screws in a paired human subaxial cervical model. Pedicle screws sustained approximately 52% higher maximum fatigue loads and endured approximately 57% more loading cycles before reaching the 5-mm displacement threshold, while retaining greater stiffness at the end of testing. By assessing progressive loosening under repetitive loading rather than monotonic axial pullout, the fatigue-to-displacement protocol provides additional insight into the durability of the bone–screw interface under cyclic loading. These findings support a substantial mechanical advantage of cervical pedicle fixation when secure pedicle screw placement is anatomically and technically feasible.

Declarations

Author Contribution

F.S.K. and L.W. designed the study. F.S.K., J.M.C. and L.W. performed the experimental work and collected the data. F.S.K. analyzed the data and drafted the manuscript. K.J., F.E.R., J.R. and M.P.M. contributed to review and editing of the manuscript. W.L. and L.W. supervised the project and critically revised the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures



Figure 1

Representative anteroposterior (a) and lateral (b) fluoroscopic images of an isolated subaxial cervical vertebra following paired placement of a cervical pedicle screw and a contralateral lateral mass screw. The images illustrate the different screw trajectories and were obtained to verify implant position before potting and biomechanical testing.

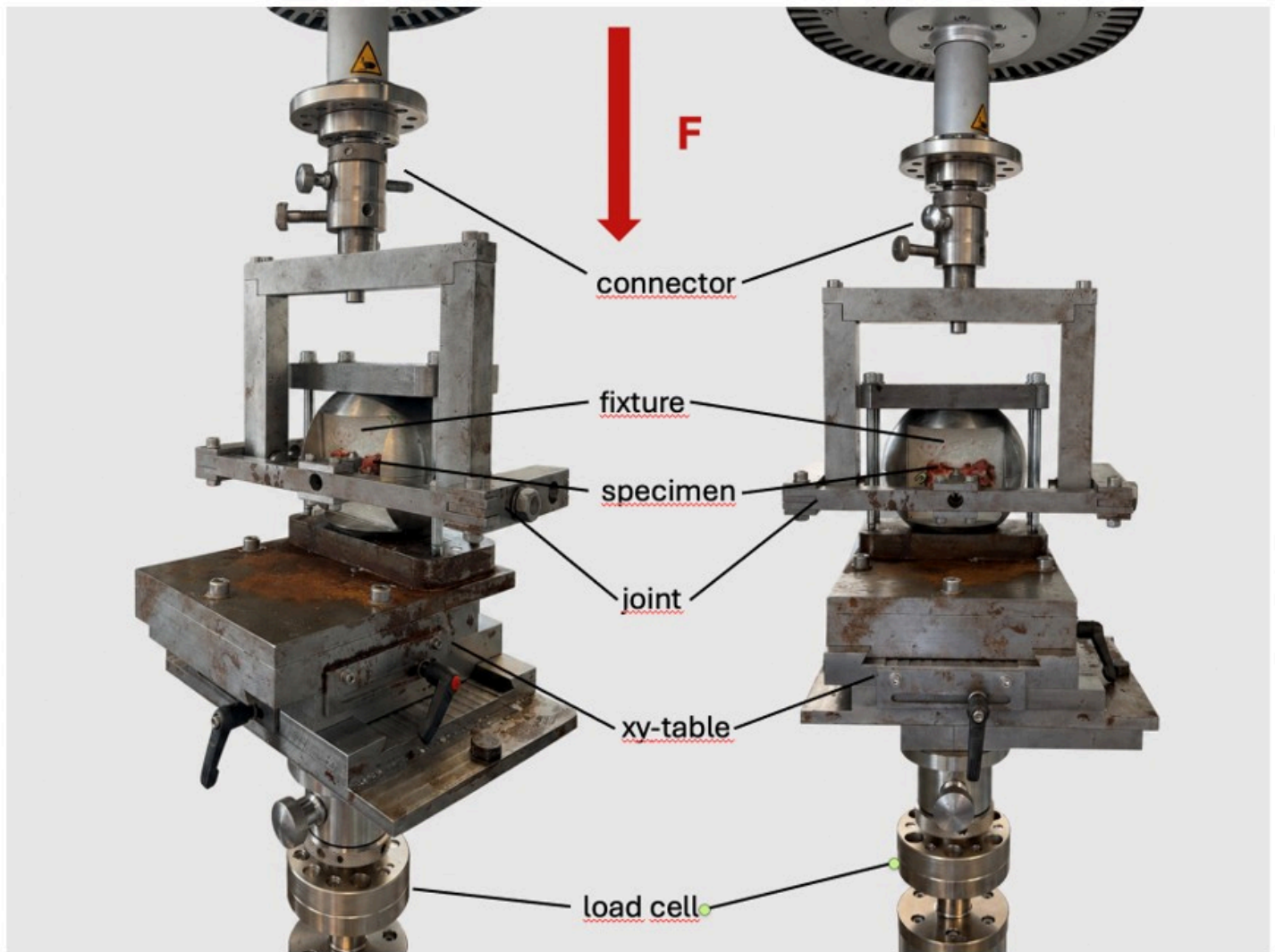


Figure 2

Experimental setup for progressive cyclic fatigue testing of cervical screw fixation. Oblique (left) and frontal (right) views demonstrate the embedded subaxial cervical vertebral specimen positioned in the custom-made spherical fixture. The screw head was coupled to the actuator through the connector and rotational joint, which allowed rotation in one degree of freedom while the remaining degrees of freedom were constrained. The fixture was positioned on an xy-table above the load cell to permit precise alignment of the screw head beneath the loading axis. The red arrow indicates the cranio-caudal direction of force application (F).

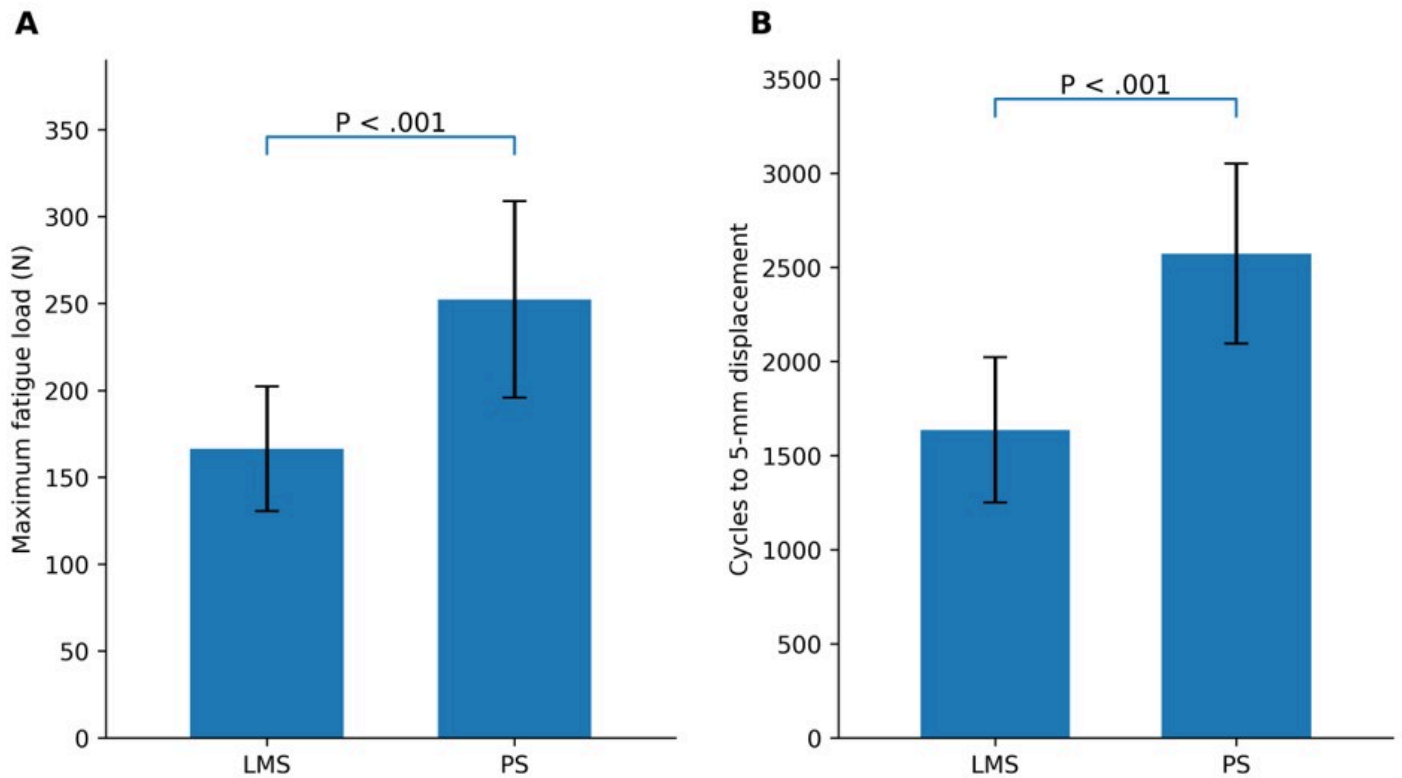


Figure 3

Comparison of the primary biomechanical outcomes between lateral mass screws (LMS) and pedicle screws (PS) in 10 paired subaxial cervical vertebral specimens. (a) Maximum fatigue load and (b) number of loading cycles required to reach the 5-mm displacement threshold. Bars represent mean values and error bars indicate standard deviation. Pedicle screws showed significantly higher maximum fatigue load (252.4 ± 56.5 N vs 166.4 ± 35.8 N) and significantly more loading cycles to 5-mm displacement (2572.8 ± 478.8 vs 1636.0 ± 386.2 cycles) than lateral mass screws (both $P < .001$).

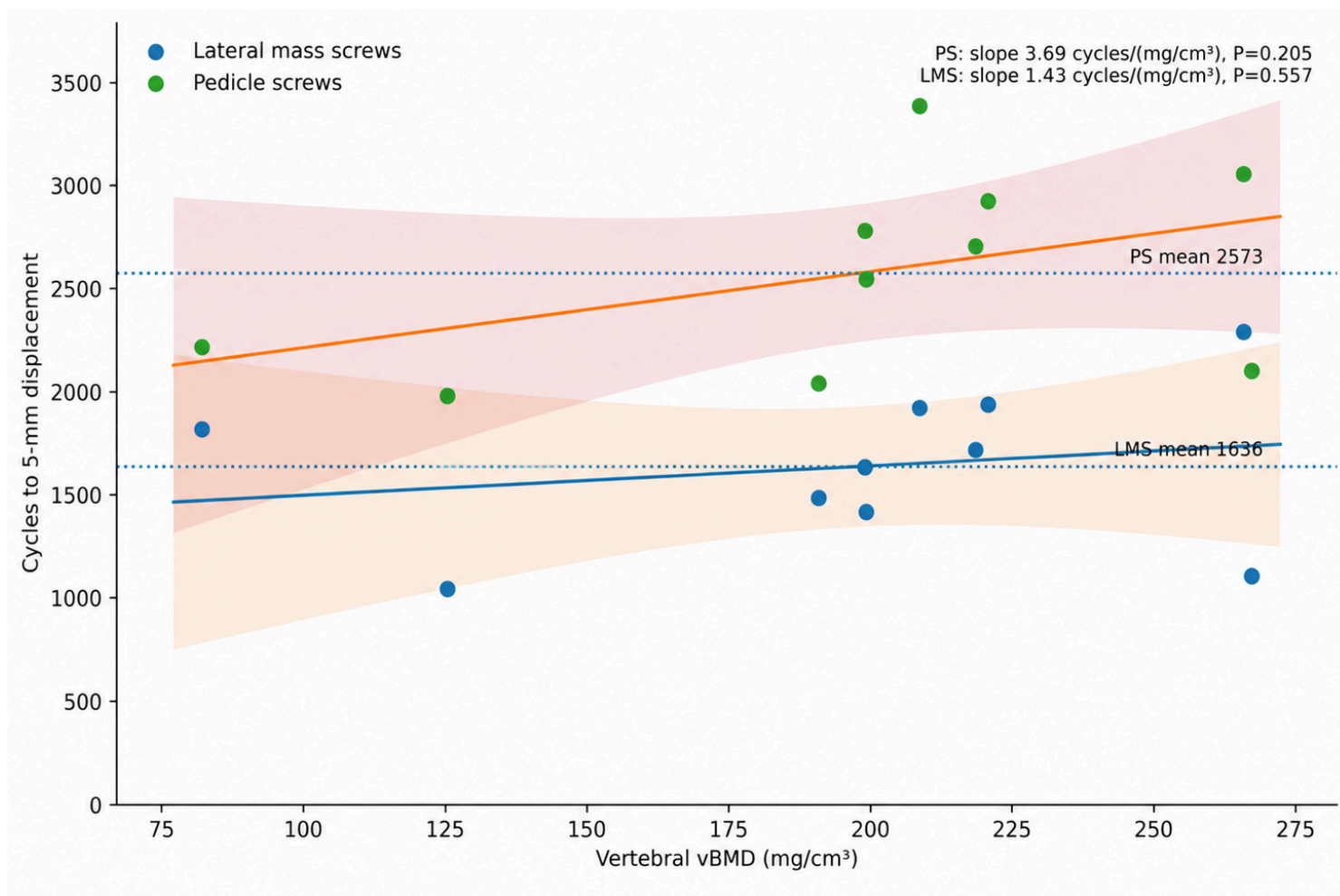


Figure 4

Relationship between vertebral volumetric bone mineral density (vBMD) and cycles to 5-mm displacement for pedicle screws (PS) and lateral mass screws (LMS). Individual data points represent the 10 paired cervical vertebral specimens. Solid lines indicate the linear regression fits, with shaded areas representing the 95% confidence intervals. Horizontal dotted lines indicate the mean number of cycles to 5-mm displacement for PS (2572.8 cycles) and LMS (1636.0 cycles). No significant association between vBMD and cycles to 5-mm displacement was observed for either PS ($P = .205$) or LMS ($P = .557$).