

# A Novel Semi-Cannulated Screw with Cement Augmentation for Revision Lateral Mass Fixation: A Cyclic Loading Biomechanical Study

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## ABSTRACT

**Purpose:** This study biomechanically compared a novel semi-cannulated lateral mass screw with cement augmentation against conventional solid screws for stabilizing loosened cervical lateral masses under cyclic loading.

**Methods:** Eight fresh human cervical specimens underwent  $\mu$ CT scanning for BMD assessment. Each specimen received both screw types: on the augmentation side, semi-cannulated screws were initially loosened via pull-out testing then reinserted with cement; on the (contralateral) primary side, conventional solid screws were placed without augmentation. After cyclic loading, vertical displacement, toggling angle, and rotation center distance (ORC) at the screw-bone interface were measured, followed by final pull-out force tests.

**Results:** The mean BMD of the lateral masses was  $305.05 \pm 48.33$  mg/cm<sup>3</sup>. Following cyclic loading, the augmentation side exhibited a significantly higher pull-out force than its initial state ( $P < 0.01$ ), though not statistically greater than the primary side. Under cyclic loading, the augmentation side demonstrated significantly superior stability: vertical displacement increased by only 6.25%, compared to a 70.69% increase on the primary side ( $P < 0.05$ ). The toggling angle decreased by 2.36% on the augmentation side, versus a significant 79.92% increase on the primary side ( $P < 0.05$ ). The ORC increased by 2.13% on the augmentation side, markedly lower than the 38.03% increase on the primary side.

**Conclusion:** The novel semi-cannulated lateral mass screw with cement augmentation demonstrated superior dynamic stability and significantly improved fixation strength after cyclic loading compared to conventional solid screws, offering a promising revision strategy for cervical spines with screw loosening or osteoporosis.

**Keywords:** Semi-cannulated screw, Cervical spine, Biomechanics, Pull-out strength, Cement augmentation, Cyclic loading.

## INTRODUCTION

Posterior cervical lateral mass screw fixation is a well-established and fundamental technique for stabilizing the cervical spine in cases of trauma, degeneration, or deformity<sup>1-3</sup>. However, the long-term success of this procedure is critically dependent on the bone mineral density (BMD) of the lateral masses. Screw loosening and subsequent pullout remain significant clinical challenges, particularly in elderly patients with osteoporosis or in revision surgery scenarios<sup>4-6</sup>. This complication can lead to a loss of correction,

spinal instability, and ultimately, surgical failure. Consequently, there is a significant clinical need for effective methods to augment screws prophylactically in osteoporotic bone or to salvage them after loosening occurs during surgery.

Polymethylmethacrylate (PMMA) cement augmentation has been introduced as a valuable technique to enhance screw fixation strength in osteoporotic bone, either prophylactically or as a rescue procedure for loosened screws<sup>7-9</sup>. While effective, traditional cement application techniques carry an inherent risk of cement leakage, which can potentially lead to catastrophic



*Fig. 1 — Screw design scheme. Schematic of the semi-cannulated screw, featuring side holes located 6 mm and 9 mm from the tip to enable directional cement augmentation.*

neurological or vascular complications<sup>1,11</sup>. To address this limitation, we developed a novel semi-cannulated lateral mass screw designed for controlled, targeted cement delivery through its cannulated body and lateral holes, while a solid head prevents cement backflow. Our previous research validates that the novel semi-cannulated screw design ensures robust fixation stability and a safer profile for PMMA augmentation<sup>12</sup>.

However, the clinical setting involves continuous cyclic loading from head weight and neck movement. Therefore, evaluating the dynamic stability of the screw-bone interface under sustained cyclic loading is of paramount clinical importance, as it more accurately simulates the in vivo environment than a simple pull-out test<sup>13,14</sup>.

The biomechanical performance of this novel cement-augmented screw under such cyclic fatigue conditions, and its direct comparison to conventional solid screws, has not been fully elucidated. It is unknown whether the superior immediate strength translates to maintained stability under repetitive stress, which is the true determinant of long-term clinical success.

Therefore, the purpose of this study was to biomechanically evaluate and compare the performance of our novel PMMA-augmented semi-cannulated lateral mass screw against a conventional solid screw in a human cadaveric model under cyclic loading. We specifically measured the vertical

displacement at the screw-bone interface, the screw toggling angle, the rotation center distance (ORC), and the ultimate post-cyclic pull-out strength. We hypothesized that the cement-augmented SC-LMS would provide significantly superior dynamic stability and sustain a higher post-cyclic fixation strength compared to the conventional solid screw.

## MATERIALS AND METHODS

### *Design of the screw*

A semi-cannulated cervical lateral mass screw was designed with an outer diameter of 3.5 mm and an inner lumen diameter of 1.1 mm. As illustrated in Figure 1, side holes were incorporated at distances of 6 mm and 9 mm from the screw tip. This geometry enables targeted cement delivery through the side ports while maintaining structural integrity by avoiding excessive proximity between adjacent holes. The screw length was standardized at 16 mm to achieve bicortical fixation.

### *Specimen Preparation*

Radiographs and computed tomography (CT) scans were obtained to screen the cervical spine specimens, ensuring the absence of deformities, pathological lesions, or structural damage from prior biomechanical testing. A total of eight cervical segments—specifically, two C3, two C4, and four C5 vertebrae—were selected for biomechanical evaluation. The specimens were

carefully disarticulated into individual vertebrae, with all surrounding soft tissues meticulously removed.

### ***μCT scanning***

Prior to screw implantation, all eight cervical specimens were aligned vertically in a tube and subjected to high-resolution  $\mu$ CT scanning ( $\mu$ CT 80, SCANCO MEDICAL, AG, Switzerland) in accordance with established guidelines for bone microstructure analysis in cadaveric tissue. The scanning parameters were configured as follows: X-ray voltage 55 kV, current 145  $\mu$ A, total scan time 300 s, continuous rotation without interruption, four-frame averaging, 360° rotation range, and integration time 300 ms. Trabecular thickness (Tb.Th) and trabecular separation (Tb.Sp) were derived from region-of-interest (ROI) analysis to assess cancellous bone architecture. Local bone mineral density (BMD), as defined in this study, was calculated based on ROI analysis encompassing cortical and cancellous bone across bilateral lateral masses. Following PMMA injection, CT scanning was performed under the following parameters: 70 kV voltage, 200 mA tube current, 3 mm slice thickness, 2 mm slice interval, 1.5 mm spiral pitch, and 1.5 ms scanning time. All data were acquired using the manufacturer-supplied software.

### ***Specimen Implantation and cement augmentation Procedures***

The novel screw was inserted using Magerl's technique. On the augmentation side, an initial pull-out test was conducted to measure the baseline pull-out force and establish a screw loosening model in the lateral mass. The same screw was then reinserted into the loosened trajectory. Following approximately 3 minutes of mixing, polymethylmethacrylate (PMMA) cement was transferred to a customized syringe, and a volume of 0.25 mL was injected under controlled pressure.

### ***Biomechanical test***

#### ***Axial Pull-out testing***

Axial pull-out testing was conducted on the augmentation side using a Bose AT-3510 system (Bose, Electro Force Systems Group, Eden Prairie, MN, USA). Each specimen was individually embedded in polyvinyl chloride, and the screw head was secured to the loading fixture. The assembly was mounted and aligned on the material testing machine to ensure the longitudinal axis of the screw coincided with the direction of the applied load (Figure 2). A tensile force was applied along the screw axis at a constant displacement rate of 0.2 mm/min until fixation failure.



*Fig. 2 — Experimental setup for evaluating screw fixation strength.*

occurred, and the maximum load was recorded as the pull-out strength. The same testing protocol was subsequently applied to evaluate the post-cyclic pull-out strength on both the augmentation and the primary sides.

### Loading test

According to the American Society for Testing and Materials (ASTM) cervical spine load test standard recommended unilateral screw structure test method (Figure 3A), the special load module and shell were designed and produced. The load module was used to simulate the upper cervical spine and the module was connected with the lateral mass screw, a simple two-segment connection of the cervical spine was simulated. This requires our module to have biomechanical characteristics similar to bone tissue, for which we used PCDF materials to produce the module. In order to ensure that the load moment is parallel to the screw in the same direction during the loading process, and no coronal moment is generated, we designed a special shell to connect with the cavity on the load module through the cylindrical bar (Figure 3B), so that the load shell and the load module are active in the coronal plane during the loading process, and the load moment is parallel to the screw. The purpose of the load test was to calculate the relative displacement of the interface between the screw and bone during the loading process. We need to place one tracker on bone interface side and the other one on screw interface side. For the bone interface, we put the tracker under the cervical spinous process through Kirschner wire, named tracker 1. Extended interface we design a screw and nut bar connection tracking device, named tracker 2 (Figure 3C).

Following  $\mu$ CT scanning of all eight bilateral lateral masses, the specimens were prepared for embedding. The specimen connected to the load module was fixed to the base of the cyclic load testing machine through the metal test slot block embedded in the specimen. The load module and the two screws were adjusted to be perpendicular to the ground. On the load module, at an eccentricity of 3.0cm, our fatigue load application point is applied to a 50N torque 1.5nm 1000 cycle with a frequency of 0.5 Hz. The 3D motion between the side bone and screw was measured using an optoelectronic camera system (Optotrak 3020, Northern Digital Inc., Waterloo, ON) via an LED marker carrier. The posterior-superior junction of the lateral mass screw nut and the connecting rod was captured as the target virtual point by Optotrak digitizing probe. The camera system was synchronized with the Instron machine at a sampling rate of 50 Hz. During cyclic loading, data were collected at four predefined intervals: the 1st, 10th, 100th, and 1000th cycles. The vertical displacement, toggling angle, and rotation center distance (from rotation center to screw tail) were quantified and compared between the two experimental groups. In our study, with a screw length of 22.3 mm (tip to bottom), a rotation center was defined as located outside the screw if the measured distance exceeded this value ( $>22.3$  mm), and on the screw if it was less than or equal to 22.3 mm ( $\leq 22.3$  mm).

### Statistical Analysis

All statistical analyses were performed using SPSS Statistics for Windows, Version 20.0. A p-value of less than 0.05 was defined as statistically significant. Intergroup comparisons were conducted using Student's t-test for two groups. For comparisons

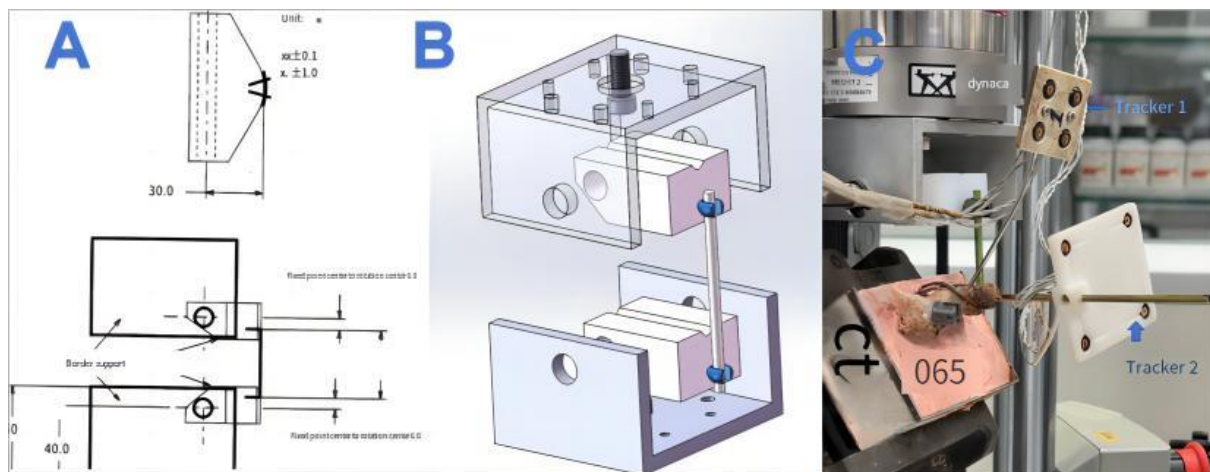


Fig. 3 — (A) Standard of ASTM; (B) Schematic diagram of loading module and loading device; (C) Tracker design and placement.

involving more than two groups, one-way or two-way analysis of variance was applied.

## RESULTS

The measured bone structural parameters are summarized in Table I. The overall mean bone mineral density (BMD) was  $305.05 \pm 48.33 \text{ mg/cm}^3$  ( $n=16$ ), with a trabecular thickness (Tb.Th) of  $307.19 \pm 34.86 \text{ }\mu\text{m}$  and a trabecular separation (Tb.Sp) of  $884.38 \pm 220.76 \text{ }\mu\text{m}$ . On the augmentation side, the BMD was  $306.85 \pm 46.34 \text{ mg/cm}^3$  ( $n = 8$ ), Tb.Th was  $371.11 \pm 25.5 \text{ }\mu\text{m}$ , and Tb.Sp was  $873.88 \pm 100.03 \text{ }\mu\text{m}$ . On the control side, the corresponding values were  $303.25 \pm 53.40 \text{ mg/cm}^3$  ( $n = 8$ ) for BMD,  $369.28 \pm 44.04 \text{ }\mu\text{m}$  for Tb.Th, and  $894.88 \pm 306.88 \text{ }\mu\text{m}$  for Tb.Sp.

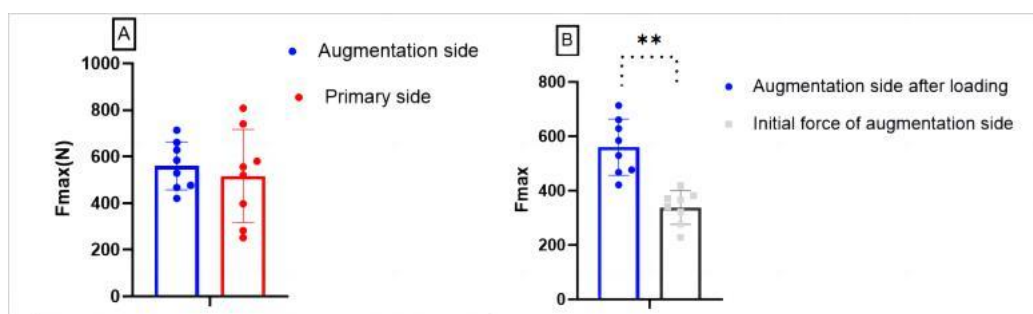
Biomechanical testing confirmed the successful creation of a screw loosening model, with an initial pull-out strength of  $338.13 \pm 61.56 \text{ N}$  ( $n = 8$ ) without causing lateral mass fracture, which established a reliable baseline for subsequent augmentation. Although the final pull-out strength after 1000 loading cycles was not statistically different between the augmentation side ( $560.46 \pm 103.34 \text{ N}$ ) and the primary side ( $517.15 \pm 199.74 \text{ N}$ ) after cycling was not statistically significant ( $P > 0.05$ ; Fig. 4A), PMMA augmentation conferred a significant restorative effect—the post-cyclic pull-out force on the augmentation side was significantly greater than its own pre-augmentation strength ( $P < 0.01$ ; Fig. 4B), indicating that cementation not only restored but enhanced the fixation in the pre-loosened trajectory.

During cyclic loading, the vertical displacement on the augmentation side consistently exceeded that on the primary side throughout the test. At the 1000th cycle, the displacements measured  $0.100 \pm 0.048 \text{ mm}$  and  $0.095 \pm 0.037 \text{ mm}$  for the augmentation and primary sides, respectively. With the exception of the 10th loading cycle, where a statistically significant difference was observed ( $P < 0.05$ ), the differences at all other time points were not statistically significant. Regarding the trend in vertical displacement change, the augmentation side exhibited an overall increase of approximately 6.25% from the initial state to the 1000th cycle, a change that was not statistically significant. In contrast, the primary side showed increases of 70.69% at the 100th cycle and 63.79% at the 1000th cycle, with the trend demonstrating statistical significance ( $P < 0.05$ ; Fig. 5A).

Throughout the cyclic loading protocol, the augmentation side exhibited a larger toggling angle than the primary side, with values of  $0.331 \pm 0.198^\circ$  and  $0.320 \pm 0.112^\circ$ , respectively, at 1000 cycles. A statistically significant difference between the two sides was observed only at the 10th cycle ( $P < 0.05$ ), with no significant differences at subsequent time points. Regarding the trend in toggling angle change, the augmentation side exhibited minimal change, showing a slight decrease of 2.36% from the initial value to the 1000th cycle; this trend was not statistically significant. In contrast, the primary side demonstrated a substantial increase of 79.92% at the 100th cycle and 23.55% at the 1000th cycle, a trend that was statistically significant ( $P < 0.05$ ; Fig. 5B).

**Table I.** — Comparison of bone quality between the two experimental sides.

|                          | Augmentation side   | Primary side        | t value | P value |
|--------------------------|---------------------|---------------------|---------|---------|
| BMD ( $\text{mg/cm}^3$ ) | $306.85 \pm 46.34$  | $303.25 \pm 53.40$  | 0.144   | 0.888   |
| Tb.Th ( $\mu\text{m}$ )  | $371.11 \pm 25.5$   | $369.28 \pm 44.04$  | 0.102   | 0.920   |
| Tb.Sp ( $\mu\text{m}$ )  | $873.88 \pm 100.03$ | $894.88 \pm 306.88$ | 0.184   | 0.857   |



**Fig. 4** — Pull-out force comparison after cyclic loading. (A) Ultimate pull-out force of the augmentation side versus the primary side following 1000 loading cycles. (B) Comparison of the pull-out force on the augmentation side before and after cyclic loading.

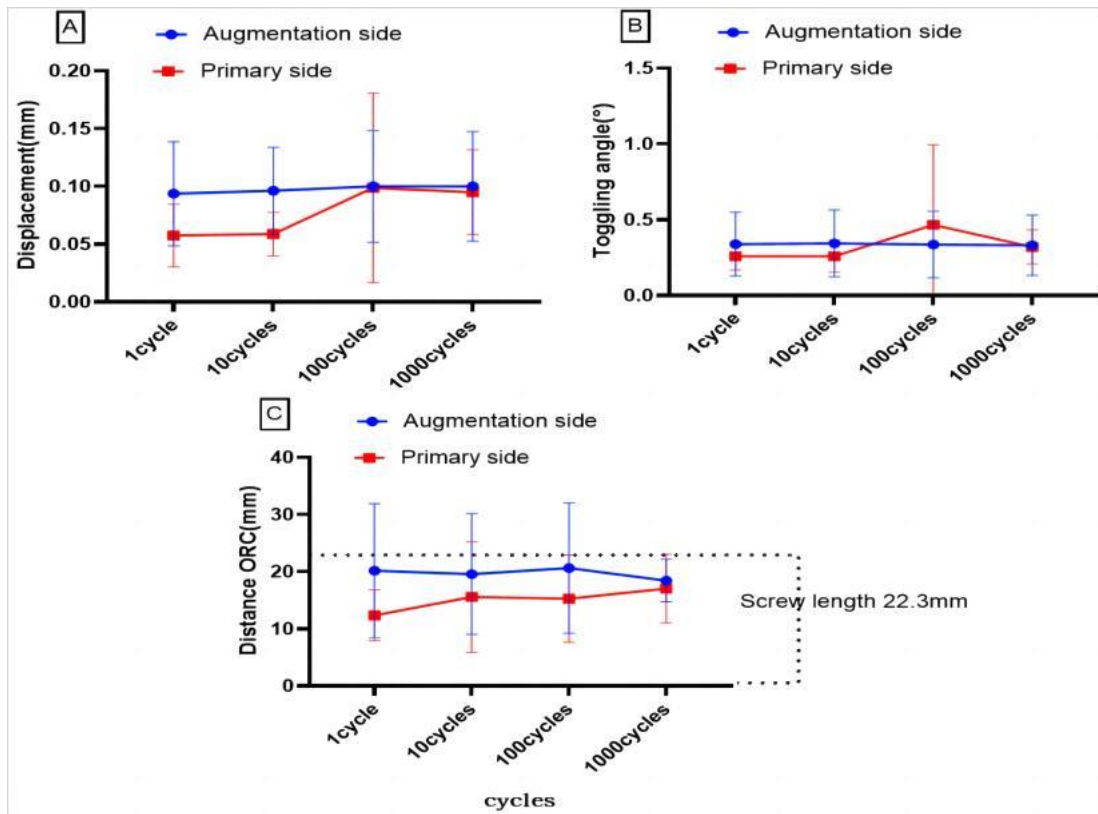


Fig. 5 — Biomechanical performance under cyclic loading. (A) Vertical displacement at the screw-bone interface on the augmentation and primary sides. (B) Screw toggling angle on the augmentation and primary sides. (C) Rotation center distance (ORC) on the augmentation and primary sides throughout the cyclic loading protocol.

Throughout the cyclic loading protocol, the rotation center distance (ORC) was consistently greater on the augmentation side than on the primary side. At 1000 cycles, the ORC measured  $18.45 \pm 3.74$  mm and  $17.06 \pm 5.99$  mm for the augmentation and primary sides, respectively; however, no statistically significant differences were observed between the two sides at any time point during the entire loading period. In terms of the change trend, the ORC on the augmentation side increased by a maximum of 2.13% from baseline to the 100th cycle, followed by a decrease toward the 1000th cycle. In contrast, the primary side exhibited

a maximum increase of 38.03% in ORC at the 1000th cycle. No statistically significant differences were detected in the trend changes between the two sides (Fig. 5C).

During the post-loading pull-out testing, we observed that the screw on the augmentation side was often extracted together with the surrounding PMMA, forming an integrated cement-screw complex. This was sometimes accompanied by avulsion fracture of the lateral mass. In contrast, no lateral mass fractures were observed during screw pull-out on the primary side (Fig. 6).



Fig. 6 — Cohesive complex formed between the screw and PMMA, accompanied by an avulsion fracture of the lateral mass.

A strong positive correlation was observed between the post-loading pull-out force and local bone mineral density (BMD) on the primary side ( $R = 0.925$ ,  $P < 0.01$ ). In contrast, no significant correlation was found between these parameters on the augmentation side (Fig. 7).

## DISCUSSION

This study biomechanically validated a novel semi-cannulated lateral mass screw with cement augmentation for revision fixation in a simulated loosening model. The principal findings robustly demonstrate the superior performance of the semi-cannulated lateral mass screw with cement augmentation under cyclic loading conditions compared to conventional solid screws, offering a promising solution for the critical challenge of screw loosening in revision cervical spine surgery.

Although the monotonic pull-out test is a standard method for evaluating the static stability of lateral mass screws<sup>15,16</sup>, it does not replicate the highly dynamic and complex biomechanical conditions experienced by spinal implants in vivo. In actual clinical use, cervical implants are subjected to repetitive dynamic loads, such as those generated by the head's weight during rhythmic activities like walking. Therefore, it is essential to evaluate the dynamic stability of cervical implants under such cyclic loading conditions, which is the primary objective of our mechanical testing. In existing fatigue tests for thoracolumbar pedicle screws, the screw is typically aligned parallel to the vertebral body and perpendicular to the direction of the applied load. This configuration allows the use of a fixed uniaxial setup to effectively simulate in vivo loading conditions<sup>17,18</sup>. In contrast, the cervical lateral mass screw is not parallel to the vertebral body and features a multi-axial screw head. Clinically, the complex loading on the implant is dispersed

through this multi-axial head, and the force is not purely perpendicular to the screw, resulting in an axial force component. To better simulate the screw's response under vertical loading while eliminating this axial component, we designed a specialized fixed-head screw and a custom loading module. This setup ensures that the applied load remains entirely vertical, thereby accurately replicating the in vivo mechanical environment. The loading parameters were selected based on biomechanical profiles of the human head and gait rhythm. A vertical load of 50 N combined with a 1.5 Nm bending moment was applied under an eccentric loading configuration, representing standard cervical spine loading conditions<sup>19-21</sup>. An eccentric distance of 3 cm was utilized, following the ASTM standard test method for unilateral cervical screw constructs.

The most striking finding was the exceptional dynamic stability of the augmentation side throughout the entire testing protocol. While exhibiting larger initial displacements and toggling angles—likely attributable to incomplete PMMA interdigitation within the pre-loosened trabecular network—the augmentation construct demonstrated remarkable long-term stability with changes of less than 7% in all measured parameters from cycle 1 to 1000. This result corroborates prior research on the screw-cement-bone construct, where interfacial reinforcement leads to significantly enhanced stability and robust load-sharing capability<sup>22-24</sup>. In stark contrast, the primary side exhibited progressive mechanical deterioration with 70-80% increases in the same parameters. The augmentation construct exhibited a fascinating trend of dynamic stabilization under prolonged cycling. Although the absolute ORC values between sides did not reach statistical significance, the diametrically opposed trends in their temporal evolution powerfully underscore the fundamental difference in fixation behavior. This suggests a progressive optimization

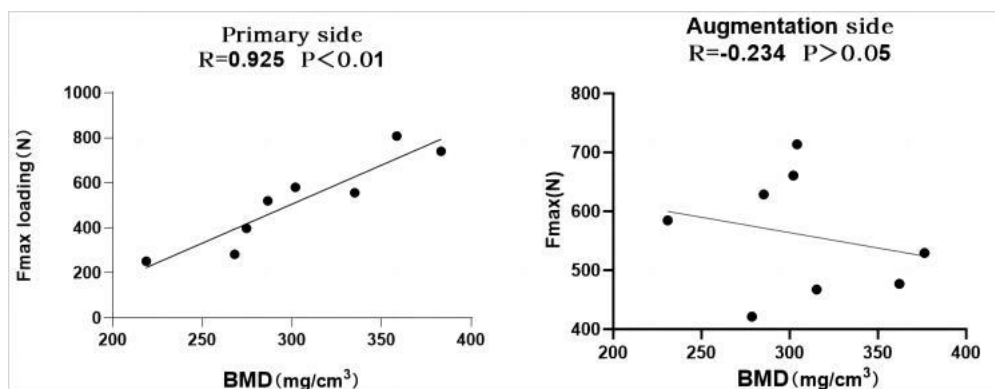


Fig. 7 — Correlation analysis between post-loading pull-out strength and local bone mineral density (BMD).

of the screw-cement-bone interface under load, culminating in its exceptional long-term stability.

Furthermore, correlation analysis provided a critical biomechanical insight: a strong dependence of post-cyclic pull-out strength on local BMD was observed on the primary side ( $R = 0.925$ ,  $P < 0.01$ ), consistent with the well-established relationship between bone quality and screw stability<sup>25-27</sup>. In striking contrast, this dependence was completely abolished on the augmentation side. This demonstrates that PMMA augmentation effectively creates a new load-bearing construct, whose strength is derived from the screw-cement composite rather than the native bone, thereby effectively compensating for poor local bone quality.

Despite these promising results, several limitations must be acknowledged. First, the use of fresh-frozen cadaveric specimens lacks the physiological blood flow present in a clinical setting, which can influence cement polymerization and interdigitation. Second, although 1000 loading cycles effectively differentiated initial performance, a higher cycle count could more clearly reveal long-term fatigue behavior and thereby identify potential late-stage failure modes.

## CONCLUSIONS

In conclusion, the novel semi-cannulated lateral mass screw with cement augmentation demonstrated superior dynamic stability and significantly improved fixation strength after cyclic loading compared to conventional solid screws, offering a promising revision strategy for cervical spines with screw loosening or osteoporosis.

*Ethics approval and consent to participate:* All procedures involving human cadaveric specimens were approved by the institutional review board of Quanzhou First Hospital Affiliated to Fujian Medical University ([2021] No. 230).

*Consent for publication:* Not applicable.

*Availability of data and materials:* The data that supports the findings of this study are available from the corresponding author upon reasonable request.

*Competing interests:* The authors declare that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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*Author Contributions:* Qingan Zhu, Dongbin Qu and Canyang Huang conceived and supervised the study. Canyang

Huang, Zhiping Huang and Zhenqiang Wang performed the experiments, analyzed the data, and drafted the manuscript. Xiuhua Wu revised the manuscript and contributed to data analysis and interpretation. All authors reviewed, revised, and approved the final manuscript.

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