

Augmented Reality Navigation for Pedicle Screw Fixation: Technical Accuracy and Feasibility in a Human Cadaveric Study

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Background: Pedicle screw fixation is the gold standard for spinal stabilization, but accurate placement remains challenging. Conventional navigation systems have limitations including workflow disruption and divided attention between the surgical field and external monitors. This study evaluates the feasibility and accuracy of a novel augmented reality navigation for pedicle screw fixation (ARNF) system in human cadaveric specimens.

Methods: Two human cadaveric specimens were used for placement of 18 pedicle screws (10 in cadaver 1, 8 in cadaver 2) across thoracolumbar vertebrae (T12–L4). A custom-developed head-mounted display with optical tracking was employed to project 3-dimensional reconstructed spine models and planned screw trajectories into the surgeon's field of view. Registration was performed using 15 anatomical landmarks with a point-pair matching technique. Accuracy was assessed by postoperative computed tomography scan, measuring entry point deviation, trajectory deviation, and angular difference, and using the Gertzbein-Robbins classification.

Results: Of the 18 pedicle screws placed, 16 (88.89%) achieved grade A accuracy (complete intrapedicular placement) and 2 (11.11%) were grade B (minor breach < 2 mm), yielding 100% clinically acceptable placement. Technical accuracy measurements revealed a mean entry point deviation of 0.17 mm (standard deviation [SD], 0.11 mm), mean tip deviation of 0.80 mm (SD, 0.33 mm), and mean angular deviation of 2.14° (SD, 0.69°). The average placement time was 3.1 minutes per screw.

Conclusions: The ARNF system demonstrated exceptional accuracy for pedicle screw placement in a human cadaveric model with high precision at critical anatomical landmarks. This technology allows surgeons to maintain visual focus on the surgical field while providing precise navigation guidance, potentially addressing key limitations of conventional navigation systems.

Keywords: Augmented reality, Cadaveric study, Pedicle screw fixation, Thoracolumbar spine, Surgical navigation

Transpedicular screw fixation has emerged as the cornerstone technique in spinal reconstruction, offering

biomechanical stability across a spectrum of pathologies including degenerative disease, traumatic injury, complex deformity, and spinal neoplasms.¹⁾ This technique provides exceptional 3-column control through a posterior approach, delivering significant advantages over alternative stabilization strategies.²⁾ Despite its widespread adoption, achieving precise screw placement remains technically demanding, with potential complications including neural element injury, vascular compromise, and construct failure resulting from malpositioned implants.³⁾

Conventional freehand techniques depend primarily

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on surface anatomical identification and haptic feedback, with documented accuracy rates fluctuating considerably from 69% to 94% contingent on vertebral region and surgeon proficiency.⁴⁻⁶⁾ This inconsistency has catalyzed the evolution of various navigational technologies. Fluoroscopy-guided methodologies improved upon freehand approaches yet still manifest breach rates of 5%–15% while subjecting perioperative personnel to cumulative radiation exposure.⁷⁾ Computer-assisted navigation employing pre- or intraoperative imaging has further enhanced placement precision to approximately 90%–95%.⁸⁾ Contemporary robotic-assisted platforms have subsequently emerged, demonstrating accuracy rates between 90% and 98%.^{9,10)} Notwithstanding these technological advancements, current navigation systems maintain inherent limitations including line-of-sight obstruction, workflow interruption, and divided attention between the operative field and remote visualization screens.¹¹⁾

Augmented reality (AR) represents a paradigm shift in surgical navigation, integrating digital information directly within the surgeon's visual field.¹²⁻¹⁴⁾ This innovation enables concurrent visualization of critical anatomical structures with projected trajectories while preserving focus on the surgical site, potentially resolving fundamental limitations inherent to conventional navigation systems.^{15,16)} AR applications in spinal surgery have progressed rapidly from experimental prototypes to regulatory-approved clinical implementations.¹⁷⁾ The synthesis of head-mounted display (HMD) technology with surgical navigation constitutes a particularly significant advancement, facilitating intuitive perception of complex spatial relationships while preserving essential visuomotor coordination.¹⁸⁻²⁰⁾

We hypothesized that an augmented reality navigation for pedicle screw fixation (ARNF) system would provide accurate pedicle screw placement while maintaining procedural efficiency. This experimental investigation evaluates the feasibility and accuracy of pedicle screw insertion utilizing our custom-developed ARNF in a human cadaveric model. The system incorporates a specialized HMD with dynamic instrument tracking and multi-dimensional visualization capabilities to guide pedicle screw insertion.

METHODS

Cadaveric specimens used in this study were obtained from the Yonsei University College of Medicine.

Experimental Design and Hardware Configuration

This experimental investigation assessed the efficacy and precision of pedicle screw insertion using our novel ARNF

platform in human cadaveric specimens. The study utilized 2 fresh-frozen human cadaveric specimens (1 male, age 67 years; 1 female, age 72 years). Specimens were preserved at –20 °C and thawed at room temperature for 24 hours prior to the procedure. Preoperative computed tomography (CT) evaluation confirmed the absence of metastatic disease, prior spinal instrumentation, or structural abnormalities that might affect screw placement. Through careful dissection, we exposed the thoracolumbar junction and lumbar spine (T12–L4) of both specimens. We maintained a realistic surgical environment by preserving relevant soft-tissue structures while ensuring adequate visualization of posterior elements. After thorough radiographic evaluation, we excluded vertebral segments showing preexisting fractures that might compromise accurate screw placement. The prepared specimens were positioned in a standard prone position on a radiolucent surgical table and immobilized.

Our ARNF system incorporated several integrated technological components: a custom-developed HMD with stereoscopic capabilities, a high-precision optical tracking array utilizing modified OptiTrack technology (NaturalPoint), and a dedicated computational workstation for real-time image rendering and navigation processing. For the instrumentation phase, we employed standard spine surgical tools including entry awls, pedicle probes, taps, and 5.5-mm titanium polyaxial pedicle screws (Iliad, Medyssey Co., Ltd.). These instruments were equipped with custom-designed infrared reflective marker arrays to enable continuous tracking within the surgical field.

Image Acquisition and Spatial Registration

Prior to the experimental procedure, both cadaveric specimens underwent thin-slice CT imaging (1 mm slice thickness) using a 64-detector CT system (Siemens Somatom Definition AS). We transferred these volumetric datasets to our pedicle screw simulator software, which reconstructed detailed 3-dimensional (3D) models of the vertebral anatomy and facilitated virtual planning of optimal screw trajectories.²¹⁾ To establish precise spatial correlation between the cadaver and its spine 3D model with screw trajectories, we implemented an advanced point-pair matching algorithm utilizing anatomical landmarks. This methodology necessitated the identification of 3 corresponding anatomical landmarks at each level between the virtual model and the cadaver. The selected reference points comprised spinous process apices and transverse process tips. This comprehensive registration protocol achieved a mean target registration error below 1.0 mm across all registration points, substantially exceeding the conventional standards for spinal

navigation systems (Fig. 1).

We secured a dynamic reference array to the T12 spinous process of each specimen to establish a stable spatial coordinate system that would compensate for inadvertent positional alterations during the procedure. The surgical instrumentation underwent rigorous calibration protocols to precisely define their spatial characteristics and tracking parameters within the navigational volume. The HMD received individualized calibration to accommodate the surgeon's interpupillary distance and visual pa-

rameters, followed by a systematic familiarization protocol to ensure optimal ergonomic utilization (Fig. 2).

The AR interface projected the reconstructed spinal anatomy and pre-planned screw trajectories in stereoscopic overlay within the surgeon's direct visual field. The system provided multiple visualization modalities including anatomical segmentation, trajectory visualization, instrument tracking, and multiplanar reconstructions (axial and sagittal) that updated in real time during navigation. Gesture recognition technology facilitated seamless transi-

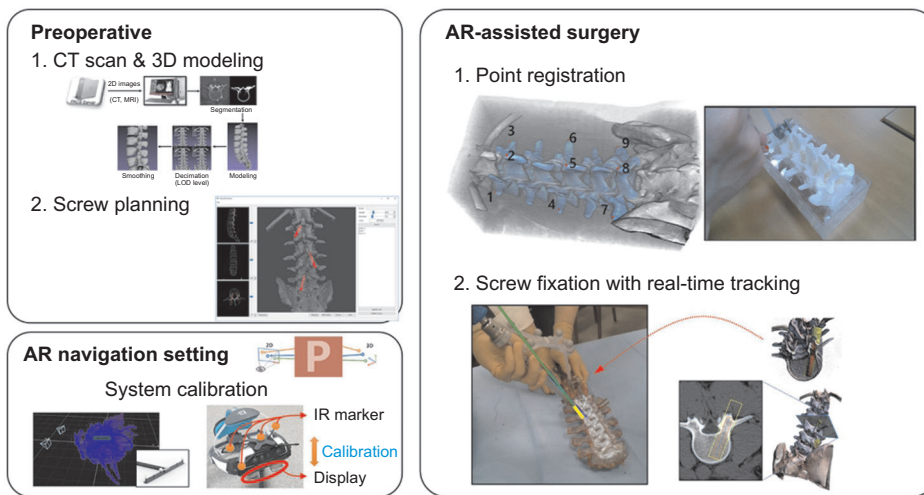


Fig. 1. Augmented reality (AR) navigation workflow for pedicle screw placement. The workflow comprises 3 main steps: preoperative planning (including computed tomography [CT] scan acquisition, 3-dimensional [3D] modeling, and screw trajectory planning), AR navigation system configuration (with system calibration and instrument tracking setup), and AR-assisted surgery (featuring anatomical point registration and real-time tracked screw insertion with multiplanar visualization). MRI: magnetic resonance imaging, LOD: level of detail, IR: infrared.

3D model → overlay

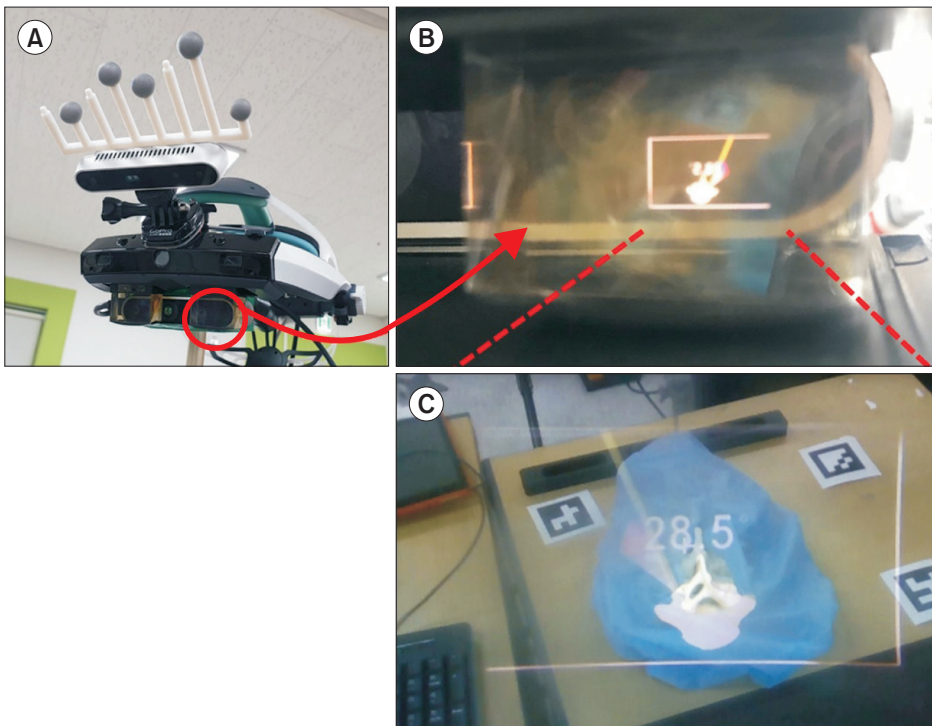


Fig. 2. Custom-developed augmented reality (AR) system for spinal navigation. (A) The head-mounted display with integrated optical tracking markers and cameras. The AR view showing real-time 3-dimensional (3D) model overlay (B) and virtual spine model with trajectory guidance (C), enabling precise surgical navigation while maintaining focus on the operative field.

tions between these visualization modalities without compromising surgical workflow.

Surgical Protocol and Performance Evaluation

An experienced spine surgeon (SMP) with more than 10 years of experience in both conventional and computer-assisted spinal fixation techniques performed all procedures. We inserted a total of 18 transpedicular screws across both specimens—10 screws in the first cadaver and 8 screws in the second—distributed throughout the thoracolumbar junction and lumbar spine (T12–L4) (Fig. 3).

The surgical technique adhered to established principles of pedicle screw fixation, modified to incorporate the AR navigational guidance. Following identification of the optimal entry point through the AR display, the surgeon created an initial cortical breach utilizing a tracked awl. A navigated pedicle probe subsequently established the transpedicular trajectory following the projected virtual pathway. After confirming the osseous integrity with a ball-tipped palpation probe, the screw pathway underwent preparation with a tap, and finally, 5.5-mm pedicle screws were inserted utilizing a tracked screwdriver.

Throughout each screw insertion, the ARNF system provided continuous real-time feedback regarding trajectory alignment, spatial deviation parameters, and potential pedicle violation risk. We documented quantitative procedural metrics including total insertion time per screw (measured from entry point identification to final screw placement) with the AR platform.

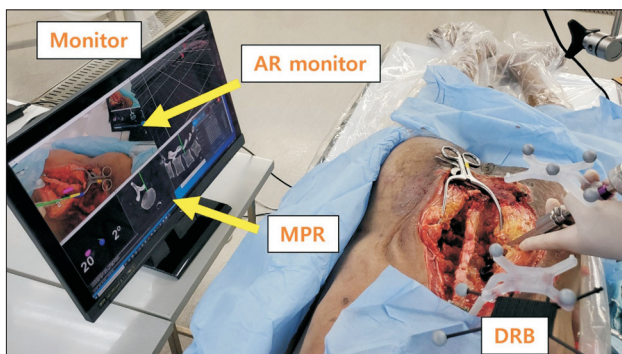


Fig. 3. Intraoperative setup demonstrating the augmented reality (AR) navigation for pedicle screw fixation system in a human cadaveric model. The AR monitor displays the AR visualization overlaying real-time multiplanar reconstruction images and the tracked surgical instruments. The dynamic reference base is securely attached to the cadaver, facilitating accurate real-time spatial tracking of surgical tools and anatomical landmarks throughout the procedure. This AR system allows the surgeon to maintain visual focus on the operative field while providing precise navigational guidance. MPR: multiplanar reconstruction, DRB: dynamic reference base.

Following completion of all screw insertions, both specimens underwent post-procedural CT imaging with identical acquisition parameters to the preoperative studies. Screw placement accuracy was evaluated by measuring entry point deviation, screw tip deviation, and angular trajectory variance between planned and actual placements.

Clinical accuracy assessment employed the validated Gertzbein-Robbins classification system, where grade A designates screws fully contained within the pedicle, grade B indicates minor breach (< 2 mm), grade C denotes moderate breach (2–4 mm), grade D signifies substantial breach (4–6 mm), and grade E corresponds to severe breach (> 6 mm).²² These measurements were conducted by an independent evaluator utilizing specialized multiplanar reconstruction software (Infinitt Picture Archiving and Communication System [PACS], Infinitt Co.) (Fig. 4). Statistical analysis was performed utilizing Stata/MP 17.1 (StataCorp.), calculating descriptive statistics for all accuracy parameters and determining both perfect placement rate (grade A).

RESULTS

Accuracy Assessment

The ARNF system demonstrated high accuracy in this human cadaveric study. Among the 18 pedicle screws placed, 16 (88.89%) achieved grade A accuracy per Gertzbein-Robbins classification, indicating complete intrapedicular placement. The remaining 2 screws (11.11%) were grade B with minor breaches (< 2 mm). No screws exhibited grade C-E breaches, yielding 100% clinically acceptable placement.

Technical accuracy metrics revealed a mean entry

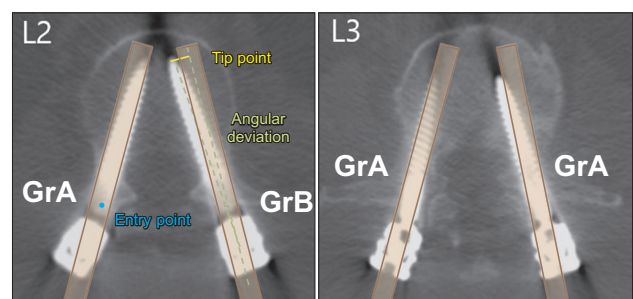


Fig. 4. Postoperative computed tomography (CT) evaluation illustrating the technical accuracy assessment method of pedicle screw placement. Axial CT images showing planned screw trajectories (orange outlines) and actual screw placements. Accuracy metrics were quantified by measuring entry point deviation (blue dot), tip point deviation (yellow line), and angular deviation (green dashed line) between planned (solid brown outlines) and actual screw trajectories. GrA: grade A, GrB: grade B.

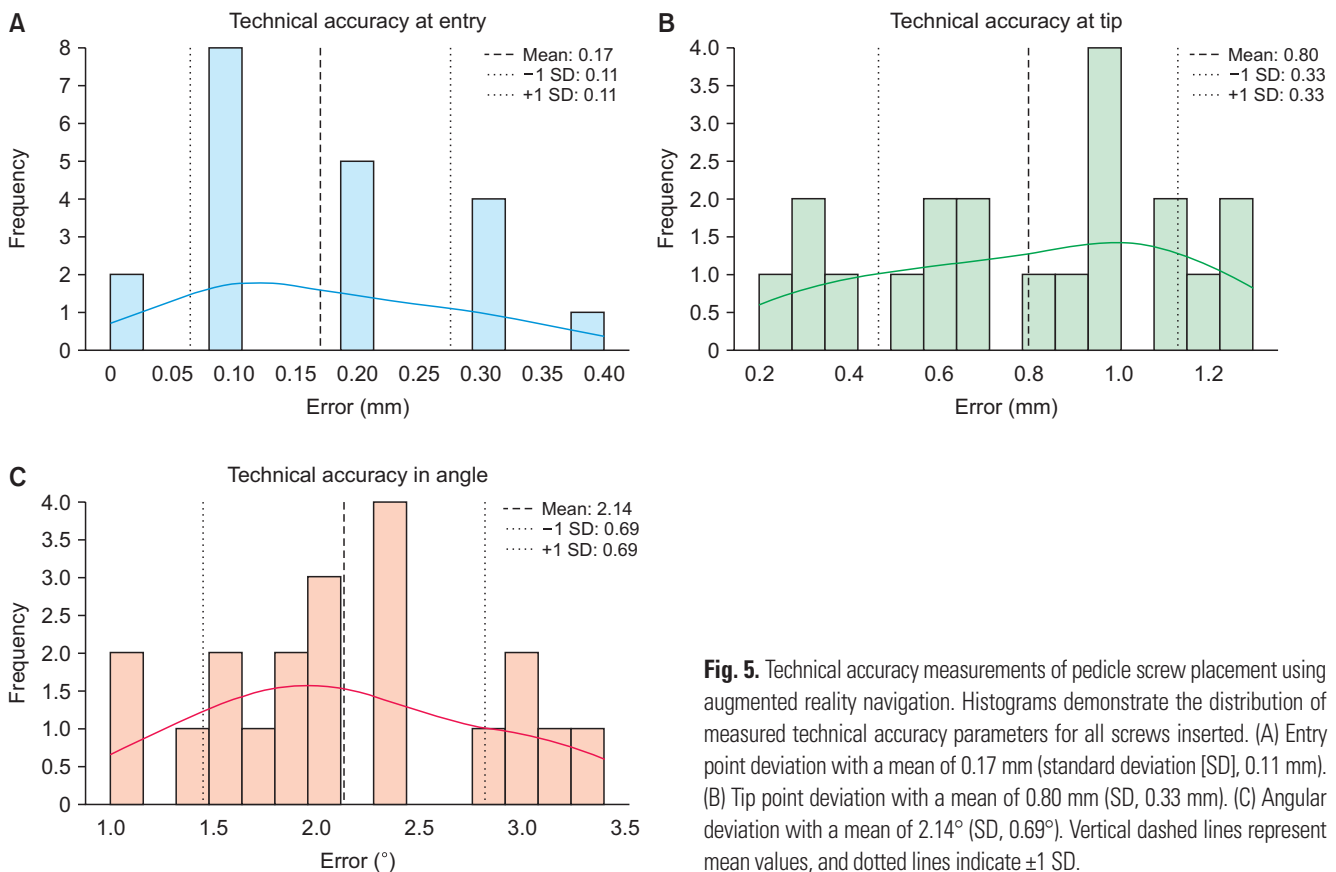


Fig. 5. Technical accuracy measurements of pedicle screw placement using augmented reality navigation. Histograms demonstrate the distribution of measured technical accuracy parameters for all screws inserted. (A) Entry point deviation with a mean of 0.17 mm (standard deviation [SD], 0.11 mm). (B) Tip point deviation with a mean of 0.80 mm (SD, 0.33 mm). (C) Angular deviation with a mean of 2.14° (SD, 0.69°). Vertical dashed lines represent mean values, and dotted lines indicate ± 1 SD.

point error of 0.17 mm (standard deviation [SD], 0.11 mm), mean tip point error of 0.80 mm (SD, 0.33 mm), and mean angular deviation of 2.14° (SD, 0.69°) between planned and actual trajectories. These values represent submillimeter spatial accuracy and minimal angular deviation throughout the screw pathway (Fig. 5).

Procedural Assessment

The mean procedural time was 3.1 minutes per screw (SD, 1.3 minutes), with an average of 1.2 trajectory adjustments required per screw (SD, 0.8). The registration process averaged 4.3 minutes per specimen. The multimodal visualization interface provided complementary spatial information that enhanced surgical navigation. No significant accuracy differences were observed between several levels, indicating consistent system performance across anatomical regions with varying pedicle morphology.

DISCUSSION

Our study demonstrates that ARNF in a human cadaveric model achieved high accuracy with 88.89% of screws placed completely within the pedicle (grade A) and 11.11%

with minor breaches less than 2 mm (grade B). The technical precision was evidenced by remarkably small deviations from planned trajectories, with mean entry point error of 0.17 mm, mean tip error of 0.80 mm, and mean angular deviation of 2.14°. These results indicate that AR guidance can potentially enhance the precision of pedicle screw placement while maintaining efficiency, with an average placement time of 3.1 minutes per screw.

The evolution of navigation technology in spine surgery has progressed from conventional fluoroscopic guidance to advanced computer-assisted systems, with AR representing the next technological frontier. Previous investigations have documented the feasibility of AR-assisted spine instrumentation. Elmi-Terander et al.^{18,23)} reported 85%–89% accuracy for pedicle screw placement in cadaveric studies, while more recent clinical applications by Liu et al.¹⁹⁾ showed 98% accuracy using an AR HMD across 205 screws. Cadaveric studies by Dennler et al.²⁴⁾ and Felix et al.²⁵⁾ demonstrated 96% accuracy and improved precision regardless of surgeon experience, findings that align with Farshad et al.'s observation²⁶⁾ that AR guidance enabled novice operators to achieve accuracy comparable to experienced surgeons. Our technical metrics compare

favorably with those reported in other AR navigation studies, including Burström et al.²⁷⁾ (angular deviations: 1.7° and 1.6°) and Molina et al.²⁸⁾ (tip deviation: 1.98 mm).

Several AR navigation systems have received regulatory clearance for clinical use, including XVision (Augmedics Ltd.). These commercially available platforms utilize automatic registration via intraoperative imaging, which offers significant advantages for clinical workflow. In contrast, our ARNF system represents an early-stage investigational platform developed entirely with domestic technology in Korea. While commercial systems have established clinical validation and regulatory approval, our study demonstrates that domestically developed AR navigation can achieve comparable technical accuracy, providing a foundation for further development toward clinically viable systems.

The clinical significance of our submillimeter entry point accuracy (0.17 mm) cannot be overstated. Precision at the initial cortical perforation phase fundamentally influences the entire screw trajectory, as entry point deviations propagate exponentially through the pedicle pathway.²⁹⁾ Similarly, our tip deviation measurement (0.80 mm) confirms that navigational precision is maintained throughout the entire transpedicular channel, which is critical for preventing iatrogenic injuries to adjacent neurovascular structures. The measured angular deviation of 2.14° falls well within established safety parameters. Rampersaud and colleagues established that maximal allowable angular deviations range from approximately 1° in the upper thoracic vertebrae to 4° in the lumbar region.³⁰⁾ Our system's performance within these thresholds suggests sufficient precision for clinical implementation across various spinal segments.

Several technological elements likely contributed to the accuracy demonstrated in this study. The immersive interface eliminated the traditional requirement for surgeons to alternate attention between the operative field and external monitors, addressing a fundamental limitation identified by Léger et al.¹¹⁾ who documented increased cognitive load and performance errors associated with visual attention shifts. Additionally, the simultaneous visualization of multi plane reconstruction facilitated immediate trajectory verification and adjustment.

The registration methodology employed in our study warrants critical analysis regarding clinical translatability. Our 15-point anatomical landmark matching protocol, while achieving high accuracy in this controlled porcine³¹⁾ and cadaveric setting, presents significant limitations for real-world surgical application. In live surgery, soft-tissue coverage obscures bony landmarks, time con-

straints limit the feasibility of extensive point registration, and anatomical accessibility is compromised compared to open cadaveric dissection. Because registration accuracy directly determines screw placement accuracy, these limitations substantially affect the interpretation of our results—the precision achieved here may not be reproducible in clinical scenarios using this registration approach.

For clinical implementation, more practical registration methods must be adopted. O-arm or 3D C-arm based automatic registration, as utilized in Food and Drug Administration-cleared systems such as XVision, offers seamless integration with minimal user intervention and has demonstrated high clinical accuracy. Surface matching techniques using intraoperative imaging represent another promising approach. Development cost constraints led us to employ the accessible point-pair matching methodology for this proof-of-concept study, understanding that this would limit clinical applicability. Future iterations of our system will prioritize integration with intraoperative cone-beam CT for automatic co-registration, which would enable both open and minimally invasive applications while maintaining acceptable registration accuracy within clinical workflow constraints.³²⁾

The current implementation of our ARNF system presents several limitations. The limited field of view in contemporary AR displays restricts comprehensive visualization of surrounding anatomical structures. While performance in the thoracolumbar region proved excellent, extrapolation to the cervicothoracic junction—with its diminutive pedicle architecture and heightened neurovascular vulnerability—necessitates dedicated investigation. Several methodological limitations must be considered when interpreting our findings. Human cadaveric models, though anatomically superior to animal specimens, lack physiological dynamics such as respiratory excursion and cardiovascular pulsation that could potentially compromise navigational precision in vivo. This study represents a preliminary proof-of-concept investigation rather than a comprehensive validation. The limited sample size (18 screws across 2 specimens) was primarily constrained by the developmental stage of our ARNF system and the associated costs of cadaveric specimens. While this sample adequately demonstrates technical feasibility, it substantially limits the reliability and generalizability of our findings. The natural variability in pedicle morphology, bone quality, and user interaction cannot be meaningfully evaluated with such limited data, and the results should not be extrapolated to expected clinical performance. Future studies with larger sample sizes involving multiple specimens and operators are necessary to establish the sys-

tem's reliability across diverse anatomical variations. Furthermore, our exclusive focus on T12–L4 segments limits direct extrapolation to other spinal regions. Accuracy achieved in the thoracolumbar region cannot be extrapolated to these more demanding anatomical zones without dedicated validation studies, as even small navigational errors in the upper thoracic spine may result in clinically significant complications. The ARNF platform, despite demonstrating promising accuracy, remains developmental and requires substantial refinement prior to clinical applications. Computational latency, optical ergonomics, and prolonged user comfort constitute essential developmental considerations. Beyond standalone navigation, AR platforms represent a fundamental infrastructure for future robotic spine surgery integration. The integration of AR with robotic systems could enable enhanced operative precision and reduced learning curves, while combining AR navigation with machine learning algorithms may facilitate real-time anatomical structure identification and predictive guidance in future applications.

This cadaveric investigation demonstrates that ARNF achieves exceptional accuracy in human specimens, with 88.89% of screws showing complete intrapedicular placement and 100% clinically acceptable positioning. The system's technical precision is evidenced by unprecedented submillimeter accuracy at both entry point and screw tip, with minimal angular deviation. The multimodal visualization interface provided by our ARNF system allowed

the surgeon to maintain visual focus on the surgical field while simultaneously accessing critical navigational data, effectively addressing the attention-shift limitations inherent to conventional navigation systems.

CONFLICT OF INTEREST

Ho-Joong Kim is an editorial board member of the journal but was not involved in the peer reviewer selection, evaluation, or decision process of this article. No other potential conflicts of interest relevant to this article were reported.

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