Robotic Thoracolumbar Pedicle Screw Fixation: A Comprehensive Narrative Review

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Abstract

Pedicle screw insertion is technically challenging and has potential complications. This, coupled with the development of minimally invasive spine surgery and the need to minimize radiation exposure, has driven innovation in navigation and robotic technologies. This narrative review aims to analyze robotic thoracolumbar pedicle screw fixation, focusing on its accuracy and various healthcare-related outcomes. Electronic databases, including PubMed and Scopus, were searched using combinations of "robotic," "pedicle screw," and "thoracolumbar." Exclusion criteria comprised studies limited to the cervical spine, case reports, non-English publications, and those solely focusing on cadaveric models, involving emerging or experimental robotic platforms. Data analysis aimed to develop subjective inferences regarding various factors concerning pedicle screw fixation and robotics. The initial search identified 139 documents, leading to 78 articles included for data extraction and assessment after screening, duplicate removal, and full-text review, with additional studies identified through bibliographic references. Comparative analyses consistently demonstrate superior accuracy with robotic-guided systems compared to three-dimensional navigation, two-dimensional navigation, and freehand techniques. Learning curves for robotic spinal surgery typically stabilize within 20–30 cases, depending on the surgeon's experience. Patients undergoing robot-assisted spine surgery experienced significantly reduced radiation exposure. Despite substantial initial capital investments, robotic spine surgery demonstrates favorable long-term cost-effectiveness in high-volume centers. Clinical outcomes are enhanced, including faster recovery, reduced pulmonary and neurological complications, and shorter hospital stays. Robotic thoracolumbar pedicle screw fixation represents a significant advancement in spine surgery. Continued research and education are essential to optimize outcomes and ensure equitable access to these advanced surgical technologies.

Keywords: Pedicle screws, robotic, spinal fusion, spine surgery

Introduction

Spinal fixation using pedicle screws and posteriorly placed rigid plates was introduced by Roy-Camille in 1979.[1] Pedicle screws secure the three columns of the spine and were a significant upgrade in grasping the vertebra when compared to the then available systems. Despite this advantage, inserting the screws is technically challenging and still carries a considerable risk of complications such as nerve damage, vascular injury, or dural tears.[2,3]

Several studies suggest that when screws are inserted free hand, as many as 30% (range: 1.7%–35%) may breach pedicle walls, often with clinical adverse effects that are not fully recognized.[4-6] Patients experiencing inadequate pedicle screw precision demonstrated prolonged recovery and increased fusion failure risk.[6,7] This knowledge gap has stimulated technological innovation aimed at enhancing pedicle screw precision.[8] Concurrently, robotic

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and navigational development was motivated by parallel advancement in minimally invasive spinal surgery utilizing percutaneous pedicle screw techniques, and accelerated by the critical need to minimize radiation exposure. SpineAssist and Renaissance systems represented pioneering robotic platforms that introduced robotic assistance for pedicle screw placement in spinal surgery. Over time, these initial-generation systems were superseded by advanced platforms incorporating optical cameras and articulated arms. The paradigm transformation occurred with second-generation systems introduced around 2016, including Mazor X, Excelsius GPS, TINAVI, and ROSA Spine. Through integration of linear optical cameras and enhanced navigation capabilities, these second-generation robots demonstrated significant pedicle screw accuracy improvements.[9,10]

The objective of this narrative review is to provide a comprehensive analysis of robotic thoracolumbar pedicle screw fixation, examining accuracy, clinical outcomes, healthcare resource utilization-related outcomes, economic implications, and future directions to guide evidence-based implementation decisions.

Materials and Methods

This narrative review was conducted through analysis of articles on robotic thoracolumbar pedicle screw fixation from 2010 to 2024. Multiple electronic databases were searched, including PubMed and Scopus. Search terms included combinations of "robotic," "pedicle screw," and "thoracolumbar." The search strategy employed a focused Boolean approach specifically targeting literature on robotic pedicle screw fixation. The comprehensive search string was constructed as: TITLE-ABS-KEY (robot*) AND TITLE-ABS-KEY ("pedicle screw") AND TITLE-ABS-KEY (thoracolumbar OR thoracic OR lumbar) AND PUBYEAR > 2009 AND PUBYEAR < 2025.

Inclusion and exclusion criteria

Studies achieved inclusion through meeting the following criteria: (1) involvement of robotic-assisted pedicle screw placement within the thoracolumbar spine, (2) reporting of clinical outcomes or technical specifications retrospectively or prospectively, (3) publication in peer-reviewed journals, and (4) inclusion of sufficient methodological detail for analysis. Exclusion criteria encompassed: (1) studies restricted to the cervical spine, (2) case reports, (3) non-English publications without adequate translation, and (4) studies focusing exclusively on cadaveric or simulation models. This review was limited to studies conducted on established robotic systems, with emerging or experimental platforms excluded from consideration.

Data extraction and analysis

Data extraction focused on: (1) accuracy rates, (2) clinical outcomes and complications, (3) healthcare resource utilization outcomes, including operative time, radiation exposure, ease of use of minimally invasive spine surgery, and need of revision surgery, (4) learning curve analyses, (5) cost-effectiveness data, and (6) technical specifications of robotic systems. Data analysis focused on developing subjective inference with regard to various factors concerning pedicle screw fixation and robotics. Data analysis focused on developing subjective inference with regard to various factors concerning pedicle screw fixation and robotics.

Results

The search yielded 233 documents based on inclusion and exclusion criteria. Following duplicate rejection and title/abstract screening, 73 studies were selected for detailed text examination. After a complete manuscript review, 28 articles were excluded, and 33 additional studies were identified through bibliographic reference review. Following the final screening, 78 articles were included for data extraction and assessment. Figure 1 depicts the article analysis and selection using a preferred reporting items for systematic reviews and meta-analyses 2020 chart. A significant increase in the publication of robotic pedicle screw fixation can be observed from 2020 onward. Substantial research has come from China, the United States, and South Korea. Statistics depicted in Figures 2–4 reveal the trends in the research around robotics in spine surgery.

Discussion

Pedicle screw fixation in the spine requires a three-dimensional (3D) orientation and skill to assess the appropriateness of the track. Freehand navigation provides a 3D orientation but poses its own challenges owing to the depth of the spine and small landmarks. The potential for straying from the planned trajectory is reduced when using a robotic arm. The use of robotic systems has the potential for future incorporation of remote surgery. Long fixation constructs and multiple surgeries in a day have the potential to increase surgeon fatigue, which can potentially be mitigated by a robot.[11,12] As compared to non-spinal procedures, spinal procedures are more intensive on radiation exposure, with as much as 10–12 fold higher radiation. This is required for accurate identification of bony landmarks and to ensure the appropriate trajectory.[13] In an effort to minimize radiation, many surgeons do not opt for minimally invasive approaches.[14,15] Presently available robots lack reliable tactile feedback and require extra training, time, and increased staff. The machinery involved is also larger and more intricate in its operation.[16] Various parameters that determine the effectiveness of robots in spine surgery are discussed.

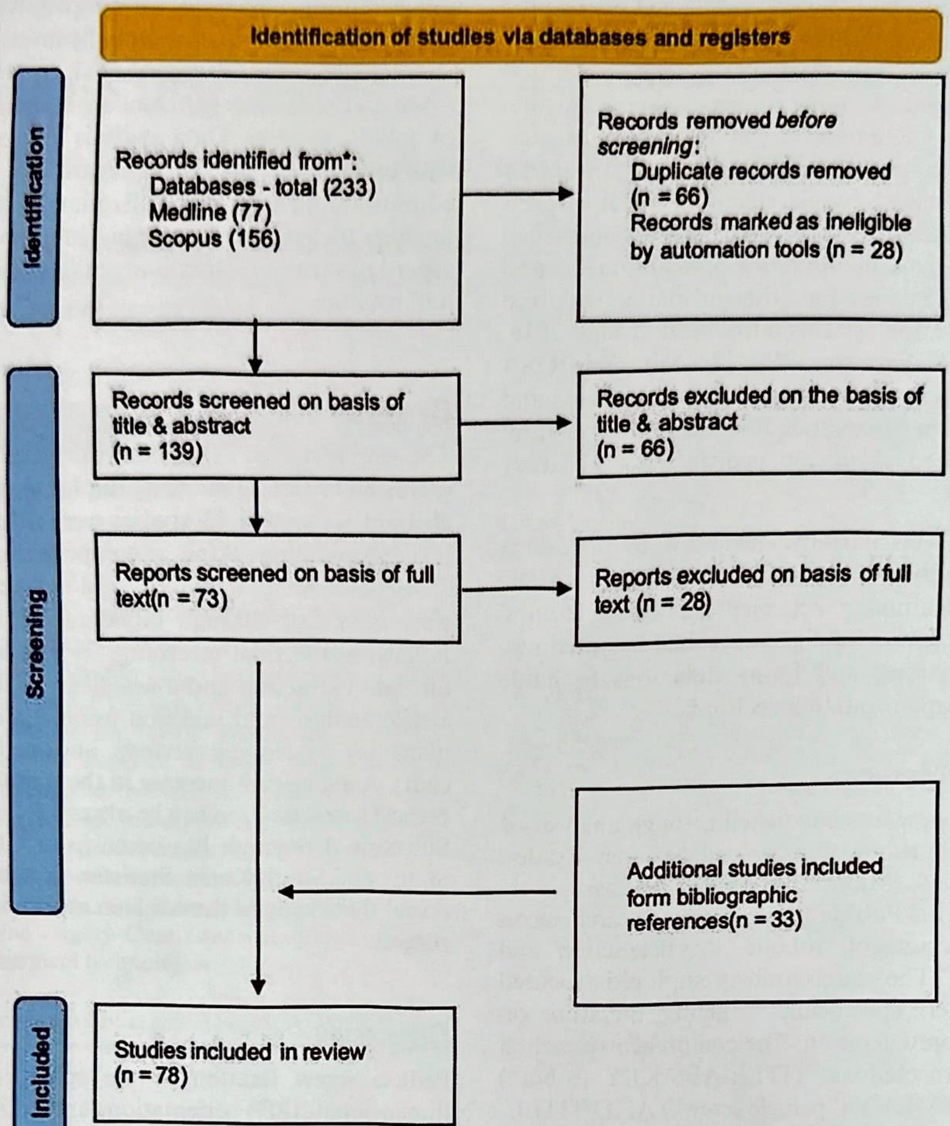

Figure 1: Preferred reporting items for systematic reviews and meta-analyses 2020 flow chart

Accuracy of robotic-guided vs. navigation vs. freehand insertion techniques of pedicle screw fixation

Contemporary comparative analyses demonstrate clear hierarchical performance differences across surgical guidance techniques. A comprehensive meta-analysis of 25,054 screws across different guidance methods revealed distinct accuracy patterns: robotic-guided systems achieved 94.2%–98.2% accuracy, 3D navigation systems reached 95.5% accuracy, two-dimensional (2D) navigation achieved 84.3% accuracy, while traditional fluoroscopy-guided (freehand) techniques demonstrated only 63.1% accuracy. Meta-analysis data reveal consistent performance across major robotic platforms: Mazor X (98.2%), Excelsius GPS (98.0%), ROSA (98.0%), and Cirq (94.2%).[17-19] Navigation systems provide intermediate performance benefits, with 3D navigation demonstrating significant improvements over 2D systems (95.5% vs. 84.3% accuracy).[19] However, navigation alone lacks the precision control and trajectory guidance provided by robotic platforms. Studies consistently show that while navigation systems improve upon freehand techniques, they do not achieve the precision levels demonstrated by robotic assistance.[9,10,20] In fact, some investigations have evaluated not only intrapedicular screw location but also assessed whether screws align with planned trajectories. Volk *et al.*[21] evaluated robotic-assisted pedicle screw placement accuracy by merging postoperative scans to preoperative plans to quantify placement precision using computerized auto-measurement algorithms. The average axial plane and sagittal plane deviations to the planned trajectory in the pedicle region for 500 screws were 1.75 ± 1.36 mm and 1.52 ± 1.26 mm, respectively. The evolution from first-generation to newer robotic systems shows dramatic improvements, with average accuracy rates increasing from 97% to 99%, respectively. Latest robots demonstrate statistically significant associations

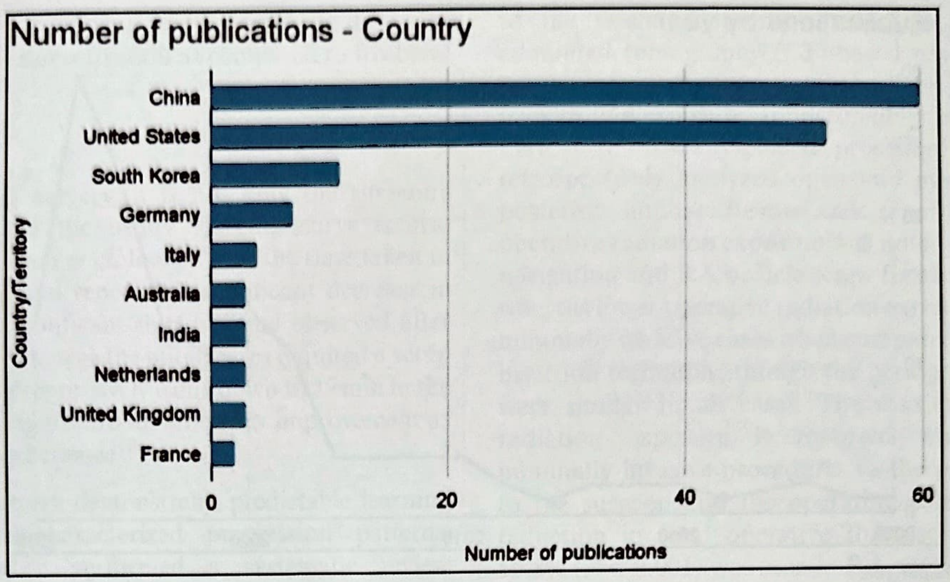

Figure 2: Number of publications country-wise

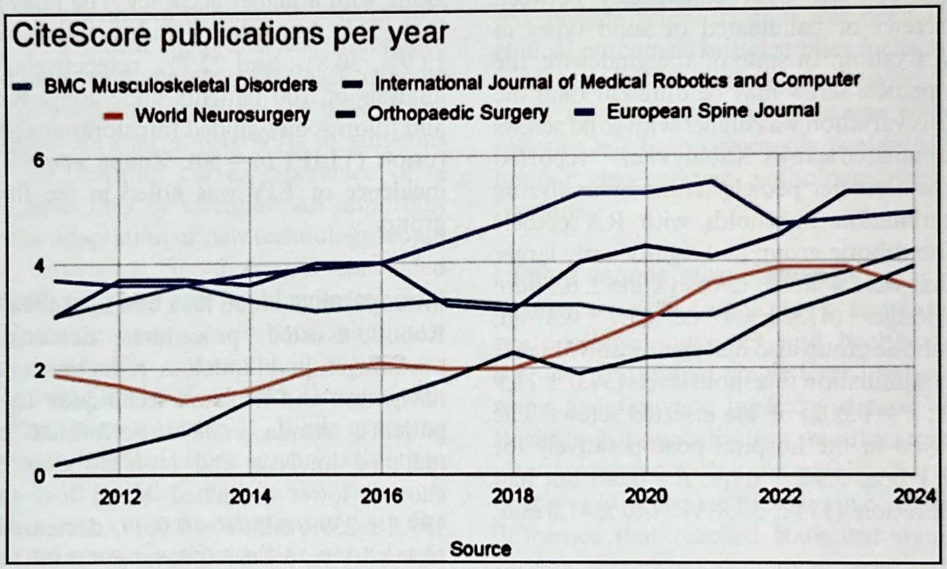

Figure 3: Year-wise cite score analysis

with improved pedicle screw insertion accuracy ($P = 0.03$), validating technological advancement investments.[10]

Impact on trajectory

Various authors have analyzed the use of robots in planning an alternative trajectory as compared to the traditional one to have a better purchase in the vertebra. Quite commonly, cortical bone trajectory (CBT) has been used in primary cases as well as cases of failed lumbar spine surgery.[22] Marengo *et al.*[23] proposed robot-assisted (RA) CBT screw placement through the muscular plane for posterior stabilization in lateral lumbar interbody fusion . The technique helps minimize soft tissue trauma and, at the same time, permits accurate CBT screw placement. This reduces the time that may be spent on changing a patient's position mid-surgery to put screws through conventional methods. An additional advantage of using the transmuscular approach is less hematoma formation.

RA screw fixation, along with endoscopic bone grafting for lumbar spondylolysis, is safe and reliable with accurate pedicle screw placement, minimizing radiation exposure and surgical trauma as compared to traditional open surgery.[24]

Werthmann *et al.*[25] described a novel workflow without the use of a tap, thus reducing a step in the workflow that used to involve three steps. They concluded that the screw insertion workflow without RA CBT reduces surgical time without increasing complications.

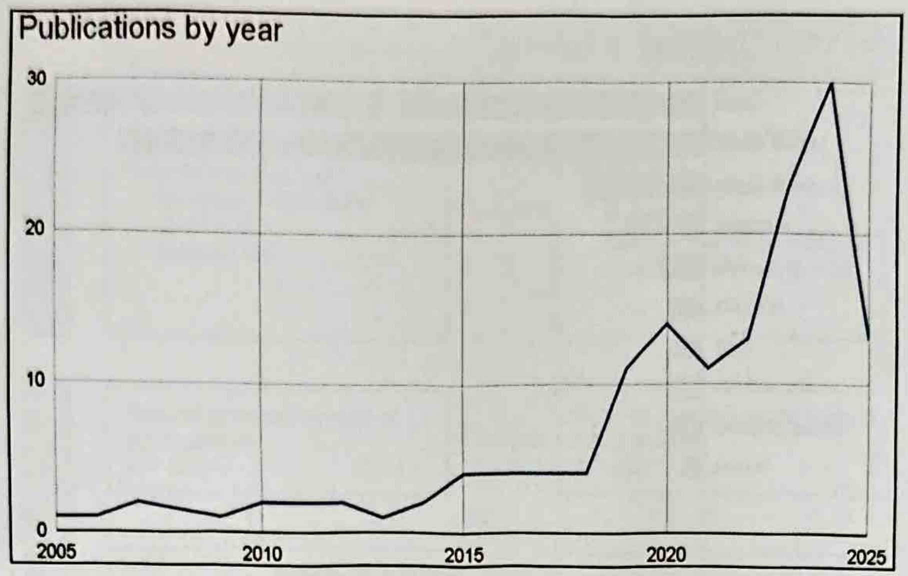

Figure 4: Publications per year

Zhao *et al.*[26] analyzed the tract consistency between guidewires and screws of cannulated or solid types in RA pedicle screw fixation. In spite of the guidewire, the trajectory of the pedicle screw may be different than the prepared tract. This variation was higher with solid screws as compared to cannulated screws. Kanaly *et al.*[27] reported safe usage of large diameter pedicle screws by analyzing pedicle screw stimulation thresholds with RA pedicle screw fixation. The robotic group had significantly larger screws inserted that were wider (7 ± 0.7 vs. 6.5 ± 0.3 mm; $P < 0.001$) and longer (47.8 ± 6.4 vs. 45.7 ± 4.3 mm; $P < 0.001$). The robotic group also had significantly higher electromyography stimulation threshold levels (34.0 ± 11.9 vs. 30.2 ± 9.8 mA; $P = 0.002$) of the inserted screws. The robotic group stayed in the hospital postoperatively for fewer days (2.3 ± 1.2 vs. 2.9 ± 2 days; $P = 0.04$) but had longer surgery duration (174 ± 37.8 vs. 146 ± 41.5 min; $P < 0.001$).

Facet joint violation

Facet joint violation (FJV) is a concerning event while putting pedicle screws that can lead to facetogenic pain as well as adjacent segment involvement in the future. Since robotic systems offer the advantage of well-planned screws, they have the potential to minimize FJV.[28] In a study assessing percutaneous thoracic and lumbar fixation, reduced FJV was noted overall, especially.[29] Nilssen *et al.*[30] in a retrospective matched cohort, concluded that use of RA lumbar pedicle screws significantly decreased the incidence of proximal FJV as compared to navigation guidance at L2 and L3 levels. Technical issues and trajectory planning likely have a role, and appropriate planning and execution should minimize FJV and proximal junctional problems. Zhang *et al.*[31] compared RA pedicle screws with fluoroscopy-guided pedicle screws and found a lower rate of cranial FJV with the robot, along with a higher accuracy. The rates of proximal FJV in the RA, fluoroscopy-guided, and freehand groups were 13.9%, 30.8%, and 22.7%, respectively. In a prospective analysis of 100 patients undergoing RA TLIF ($n = 50$) and fluoroscopy-guided transforaminal lumbar interbody fusion (TLIF) ($n = 50$), Zhang *et al.*[32] reported higher incidence of FJV was noted in the fluoroscopy-guided group.

Intraoperative blood loss and operative time

Robotic-assisted procedures demonstrate significant advantages in blood loss reduction compared to both navigation and freehand techniques. In a group of 1633 patients, Asada *et al.*[33] performed propensity score matched analysis and reported that the robot group showed lower estimated blood loss (418.9 ± 398.9 vs. 199.2 ± 239.6 mL; $P < 0.001$), decreased length of stay (4.1 ± 3.1 vs. 3.2 ± 3.0 days; $P < 0.001$) and insignificant difference in operative duration (212.5 vs. 222.0 min; $P = 0.151$) as compared to freehand group. Sun *et al.*[34] conducted a meta-analysis across 20 randomised controlled trials (RCTs) and found that blood loss during surgery was less in the RA surgery group as compared to the freehand group. Studies analyzing open and percutaneous short lumbar fusions report increased radiation exposure, but shorter operative durations and lower blood loss during surgery.[35,36] Operative time comparisons reveal complex patterns dependent on surgeon experience and case complexity. During the learning curve period, robotic procedures require 15%–25% longer operative times, primarily due to setup and planning requirements. However, experienced surgeons demonstrate 8%–15% reduction in surgical time, particularly for complex multi-level procedures.[37,38] Zawar *et al.*[39] in their review noted that only 13 studies reported decreased operative duration, whereas 17 studies showed increased operative time, with the rest of 16 studies showing no difference with the use of robots for pedicle screw fixation as compared to freehand techniques.

Learning curve

For robotic spine surgery, it is not only the surgeon's learning curve, but the team's learning curve is also important. Sundaram *et al.* looked into the time taken in the robotic setup and reported a significant decrease in duration, with a significant shift in trend observed after the first 20 cases. Whereas the initial cases required a setup time of 24 min, it progressively came down to 17 min in the later cases, pointing toward an efficiency improvement as the team gained experience.[40]

Robotic spine surgery demonstrates predictable learning curves with well-characterized progression patterns. Pennington *et al.*[41] performed a systematic review analyzing 21 articles on learning curves in robotic spine surgery. Their analysis revealed that, on average, 20–30 cases or 15–62 screws are needed to establish competency. Contrasting this, in a recent meta-analysis, McNamee *et al.*[8] concluded that approximately 60 cases may be essential for 50% of surgeons to achieve the bulk of the learning curve. To ensure that at least 90% of surgeons achieve 80% of the learning curve, experience of a larger number of cases may be essential. An important consideration for the adaptation of new technology would be the surgeons' experience. Shahi *et al.*[42] concluded that well-experienced surgeons can be expected to have no or minimal learning curve for robotic minimally invasive TLIF, in contrast to early attendings who are likely to have a learning curve of around 21 cases with the attainment of proficiency at case 31. While assessing the junior surgeons starting their spine surgery training in an RCT, Feng *et al.*[43] concluded that the RA technique allowed a short learning curve in comparison with the freehand insertion technique, with excellent results even in the initial application periods. Yu *et al.*[44] analyzed the learning curve using the cumulative sum analysis technique and reported that to pass the learning phase, a surgeon needs to perform 17–18 cases of RA pedicle screw placement. Following this, there is a reduction in the operative duration as well as an improvement in accuracy.

Fluoroscopy times

An increased risk of oncological issues has been noted among surgeons and operating room staff linked to the level of radiation exposure. Concerns have been raised by several studies over radiation exposure to the patient while using technologies such as robots and image-guided navigation, weighing it against the reduction of intraoperative radiation exposure.[45,46] In a meta-analysis, Fatima *et al.*[47] reported that cumulative radiation exposure to the patient is much less while using robotic pedicle screw placement as compared to the freehand insertion technique. Intraoperative computed tomography (CT)-based navigation exposes patients to radiation equivalent to 4.35 years of background exposure, approximately three times higher than a fluoroscopy-guided procedure. Wang *et al.*[46] retrospectively analyzed open and minimally invasive posterior lumbar fusion and reported that higher operative radiation exposure was noted in image-guided navigation and RA pedicle screw fixation in open cases, whereas lower operative radiation exposure was noted in minimally invasive cases when compared to the freehand insertion technique, though the perioperative outcomes were similar in all cases. The maximum amount of radiation exposure is reported with fluoroscopic minimally invasive procedures to the patient as well as to the surgeon and the operating room personnel. A reduction in total operative fluoroscopy duration of 50.8% ($P < 0.001$) was seen in RA surgery.[48]

Translation into clinical outcomes

RA pedicle screw fixation has been found to improve clinical outcomes. Initial studies focused mainly on screw accuracy, but several recent articles have highlighted faster recovery. Some of the areas where the impact of robotics has been commonly evaluated are surgeries for lumbar degenerative pathologies and thoracolumbar fractures.

Lumbar degenerative pathologies

Maman *et al.*[49] conducted a comparative analysis of postoperative outcomes and healthcare costs between RA and traditional single-level lumbar fusion surgeries using a nationwide inpatient dataset of 461,965 cases. Regarding hospitalization metrics, robotic procedures were associated with a marginally shorter average length of stay—3.06 days vs. 3.13 days in conventional surgery—a difference that reached statistical significance. Robotic surgery was also linked to reduced incidences of heart failure, acute coronary artery disease, pulmonary edema, venous thromboembolism, and traumatic spinal injury, all statistically significant findings. However, patients undergoing robotic procedures experienced higher rates of postoperative anemia and a greater need for blood transfusion. While the prevalence of chronic renal disease was comparable preoperatively, acute kidney injury occurred slightly more frequently in the robotic cohort following surgery. In a retrospective analysis, Tong *et al.*[50] reported that navigation RA lumbar TLIF with internal fixation, when compared to the conventional fluoroscopy-guided approach, was associated with reduced short-term postoperative low back pain, minimized surgical trauma, decreased intraoperative blood loss, and lower radiation exposure. Additionally, the robotic method achieved greater pedicle screw placement accuracy and fewer FJV, ultimately contributing to improved clinical effectiveness and enhanced safety outcomes.

Adult spinal deformity

Vengasarkar *et al.* retrospectively looked at patients with adult spinal deformity and found that robotic assistance improves short-term outcomes, including reduced rates of pulmonary complications like atelectasis, pneumonia, pleural effusion, and respiratory failure, as well as neurologic complications such as spinal cord deficits. Additionally, robotic assistance leads to shorter hospital stays.[51] Historically, minimally invasive long-segment fixation for adult spinal deformity surgery has been considered laborious and technically intensive. However, Pham *et al.*[52] demonstrated that preoperative robotics planning facilitates the design and placement of even complex multi-rod sacro-pelvic fixation for minimally invasive deformity surgery. Yang *et al.*[53] conducted a comparative analysis and found that RA percutaneous pedicle screw placement offers advantages over fluoroscopy-guided percutaneous pedicle screw placement. These advantages include greater accuracy, lower incidences of screw penetration of the pedicle wall and invasion of the facet joints, and better screw insertion angle in lumbar spondylolisthesis. Haider *et al.*[54] reported that the Mazor X-Align™ software is accurate in the projection of postoperative segmental lumbar lordosis based on preoperative radiology after a short segment fusion.

Use of robots in lateral and anterior approaches

Lateral and anterior approaches necessitate a change of patient position. Utilizing a robot for lumbar fixation helps to eliminate the need to reposition the patient, thus reducing the duration of anesthesia and enhancing efficiency.[55] In a retrospective analysis of 17 patients who underwent anterior lumbar interbody fusion (ALIF) in a single position at L5–S1, along with RA pedicle screw placement simultaneously by another surgeon, Hernandez *et al.*[56] reported the procedure to be safe as well as effective, contributing to improvement in spinal alignment and lumbar lordosis. Several papers report the beneficial outcome of RA pedicle screw fixation while utilizing a lateral corridor.[57-61] Various authors have combined the Da Vinci surgical robot for ALIF along with the RA pedicle screw fixation (PSF). Thus, the possibility of future collaborations for better circumferential fusion is being explored.[56,62]

Thoracolumbar fractures

Analyzing a group of patients undergoing RA pedicle screw fixation in thoracolumbar burst fractures, Liu reported a reduction in surgical time, decreased intraoperative hemorrhage, and improved accuracy of screws, facilitating better reduction. Short-term functional recovery was similar between both freehand and RA groups.[63] Xiao *et al.*[64] compared robotic artificial intelligence (AI)-assisted and manual placement of pedicle screws in thoracolumbar fractures and found that patients who underwent RA PSF had lower hospital stays, lower complication profile, and better Visual Analog Scale (VAS) score($P < 0.05$), though at the end of 1 year, no significant difference in VAS score was observed. Li *et al.*[65] concluded that, as compared to fluoroscopic-guided surgery, RA pedicle screw fixation surgery delivers higher accuracy and single-shot success rates of pedicle screw fixation in thoracolumbar fractures, with comparable clinical outcomes. Results of a similar nature have been observed by several different authors in thoracolumbar burst fractures.[66] Ankylosing spondylitis results in distortion of bony anatomy and leading to non-identifiable landmarks. Ye *et al.*[67] reported the surgical outcomes of RA percutaneous fixation for thoracolumbar fractures in ankylosing spondylitis patients. Among 108 screws, 2 (1.9%) were malpositioned. A delayed nerve dysfunction was observed in one patient post-surgery, which recovered in 5 days' time. They concluded that though RA pedicle screw placement enhances the pedicle screw placement accuracy, secondary measures to confirm placement should be incorporated. Hardigan analyzed the feasibility of RA minimally invasive spinopelvic fixation in post-traumatic sacral fractures in seven patients and found it a safe treatment option with the possibility of improving outcomes.[68]

Adolescent idiopathic scoliosis

A comparative analysis on RA and fluoroscopy-assisted pedicle screw placement in adolescent idiopathic scoliosis found that robots can improve the accuracy of screws and reduce the operative duration as well as the radiation exposure.[69]

Osteoporosis

Osteoporotic vertebrae have a higher chance of blowout after screw track creation or the screw and track being different. This highlights the manual "error" that may potentially be minimized by a robotic rigid arm. Feng *et al.*[70] analyzed pedicle screw fixation in the lumbar spine in osteoporotic patients. RA technique improved the screw placement accuracy (98.5% [199/202]) as compared to the freehand insertion technique (91.6% [206/225]) ($P < 0.05$).

Tumor surgery

Menta *et al.*[71] assessed the efficacy of RA pedicle screw fixation in metastatic patients and found it to be safe and efficacious even in such high-risk cases. Robots can benefit by augmenting the accuracy of pedicle screws in patients with metastatic disease. Similarly, Park[72] reported that RA percutaneous iliac screw placement was efficacious even in destructive metastatic lesions.

Comparison and cross-platform syncing

In a retrospective analysis of patients with thoracolumbar or sacral fractures undergoing surgical stabilization with RA percutaneous pedicle screw fixation, Schroeder *et al.*[73] reported a cross-platform syncing of robotic flat panel 3D C-arm (ArtisZeego) and robotic guidance by Renaissance (Mazor Robotics) in a specialized hybrid OR. Du *et al.*[74] analyzed radiological and clinical variation in RA pedicle screw fixation with and without real-time optical tracking. Robots used were of the Tinavi group (with optical tracking) and the Renaissance group (without optical tracking), according to assisted technology. The accuracy of perfect and clinically acceptable pedicle screws in the Tinavi group was 94.9% and 98.7%, while it was lower in the Renaissance group, it was 91.2% and 94.5%, respectively. Optical tracking in RA pedicle screw fixation increases accuracy due to the ability to detect the real-time position of the patient. Li *et al.*[75] in a meta-analysis on the clinical outcomes of RA spine surgeries noted that fluoroscopy time was lower in surgeries assisted by Mazor robots but higher in Tianji robots and ROSA robots.

Cost-effectiveness analysis

Despite substantial initial capital investments ($550,000–$1.5 million), robotic spine surgery demonstrates favorable long-term cost-effectiveness profiles. The landmark 2018 analysis of 557 thoracolumbar cases projected immediate conservative savings of $608,546 annually. The cost breakdown revealed: revision surgery avoidance ($314,661), reduced hospital stays ($251,860), infection prevention ($36,312), and operative time savings ($5713).[76] Return on investment calculations vary based on case volume, with high-volume centers (>200 cases annually) typically achieving break-even within 2–3 years. The economic model improves substantially with broader robotic utilization across multiple spine subspecialties, with systems capable of cervical, thoracic, and lumbar applications demonstrating enhanced cost-effectiveness. However, learning curve periods involve temporary productivity reductions and potential complication increases. Maintenance costs, software updates, and disposable supplies represent ongoing expenses, with annual maintenance contracts typically ranging from 8% to 12% of the initial purchase price and disposable costs averaging $1000–$1500 per case.[77] In contrast to this, Ezeokoli *et al.* performed a comparative analysis of 39 cases each of freehand spinal fusion and RA spinal fusion and reported that robots in spinal procedures increase the overall expense.[78] Arguments against the utilization of robots in spine surgery focus on the exorbitant cost, which is not offset by the conservation of expenses in a lesser risk of surgical site infection, reduced length of stay, and lower incidence of revision surgeries to reposition misplaced screws.[79] Per-surgery charges demonstrate a higher cost incurred with robotic spine surgery, averaging $154,673, in comparison with lower charges of $125,467 with non-robotic surgeries.[49]

Implementation recommendations and best practices

Based on the evidence presented, successful robotic program implementation requires systematic approaches addressing multiple domains:

Training and Education: Structured programs incorporating simulation, cadaveric training, and proctored cases with clear competency milestones at 25–30 cases.

Patient Selection: Emphasis on complex anatomy cases, revision surgery, and minimally invasive procedures where robotic benefits are maximized, with careful consideration of patient-specific risk factors.

Infrastructure Development: Adequate operating room space, imaging integration, and technical support with protocols for equipment maintenance and troubleshooting.

Quality Assurance: Systematic outcome tracking, complication analysis, and continuous improvement protocols to optimize program success and maintain competency.

Limitations

Several important limitations require acknowledgment. Many studies are retrospective with relatively short follow-up periods, limiting long-term outcome assessment. The learning curve studies, while consistent, are predominantly single-center experiences that may not generalize universally.

Future directions

Future research priorities include the following: prospective multi-center studies with standardized outcome measures and extended follow-up periods; head-to-head comparisons between robotic platforms using uniform patient populations; comprehensive patient-reported outcome assessments; and clinical validation studies for AI applications in surgical planning and execution.

The integration of machine learning and AI represents the next incoming winds of change in robotic spine surgery. Current developments in automated anatomical recognition, trajectory optimization, and predictive modeling promise to further enhance accuracy while reducing planning time. Augmented reality integration offers revolutionary potential for surgical visualization and guidance, with early studies demonstrating effectiveness in real-time surgical assistance.[80] Since CT is associated with significant radiation, the incorporation of other imaging modalities, such as magnetic resonance imaging, will avoid patient radiation. Though there has been development of software that assesses the rods and lordosis, to make the process more impactful, automatic planning and construct execution need to be inculcated. Some platforms that do not integrate robots and real-time navigation will need to develop a seamless workflow where both communicate in real-time. Also, the present systems are bulky and lead to operational difficulties, therefore a need to develop compact systems to improve efficiency. To make technology accessible and affordable to all, focus on enabling the safe and cost-effective integration of robotic thoracolumbar pedicle screw fixation in low-resource settings is paramount. Key priorities include the development of lower-cost robotic platforms, modular or shared-use systems, and hybrid workflows that combine robotics with conventional fluoroscopy to reduce capital and maintenance costs. Strategic partnerships between industry, academic centers, and global health organizations may further facilitate technology transfer and sustainable adoption while ensuring equitable access to robotic spine surgery.[76]

Conclusion

Robotic thoracolumbar pedicle screw fixation represents a significant advancement in spine surgery, offering demonstrable improvements in accuracy, safety, clinical outcomes, and healthcare resource utilization outcomes, including shorter operative times, reduced blood loss, and decreased hospital stays. The evidence supports adoption in appropriately selected patients and institutional settings. Successful implementation requires attention to learning curves typically stabilizing at 25–30 cases, comprehensive training programs, and systematic quality assurance protocols. The economic benefits, while requiring substantial initial investment, demonstrate favorable long-term cost-effectiveness in high-volume centers through reduced complications and improved efficiency.

As robotic technology becomes more accessible and cost-effective, it is positioned to become the standard of care for complex thoracolumbar procedures. However, continued research, education, and quality improvement efforts remain essential to optimize outcomes and ensure equitable access to these advanced surgical technologies.

Ethical policy and Institutional Review Board statement

Not applicable.

Author contributions

Study concept and design and critical revisions of article—HSC, VS. Data acquisition, analysis, or interpretation—SS, VS, AM. Drafting or critically revising the article for important intellectual content—AM, SS, VS. Final approval of the version to be published—HSC, VS. Manuscript has been read and approved by all authors, and each author believes that the work is honest.

Data availability statement

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Conflicts of interest

There are no conflicts of interest.

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