Comparative Outcomes of Robotic-Assisted And Fluoroscopy-Guided Pedicle Screw Placement In Lumbar Degenerative Disease: A Systematic Review And Meta Analysis

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Abstract.
Introduction: Pedicle screw fixation is a cornerstone of lumbar spine surgery, but fluoroscopy-guided placement is associated with screw malposition, cortical breach, facet joint violation, and radiation exposure. Robotic-assisted techniques have been developed to improve trajectory planning, placement accuracy, and procedural safety. This systematic review and meta-analysis compared robotic-assisted and fluoroscopy-guided pedicle screw placement in spinal surgery, with emphasis on accuracy and perioperative outcomes. Materials/Methods: A systematic search of PubMed and ScienceDirect was conducted for studies published between 2022 and 2025 using keywords related to fluoroscopy, robotic assistance, spine, and pedicle screws. Retrospective cohort and retrospective comparative studies evaluating robotic-assisted versus fluoroscopy-guided pedicle screw insertion were included. Outcomes included screw placement accuracy, intraoperative blood loss, radiation exposure, complications, and hospital-related outcomes. Meta-analysis was performed using Review Manager 5.3. Odds ratios were used for dichotomous outcomes, while mean differences or standardized mean differences were used for continuous outcomes. Results: Five retrospective studies involving 710 patients and 4,434 pedicle screws were included. Robotic-assisted placement demonstrated significantly higher screw accuracy than fluoroscopy-guided placement, involving 1,937 robotic screws and 2,497 fluoroscopy-guided screws. The pooled analysis showed that robotic assistance was associated with greater odds of accurate screw placement (OR 2.73; 95% CI 1.50–4.97; $p = 0.001$), although heterogeneity was moderate to substantial ($I^2 = 66\%$). Blood loss was lower in the robotic group by 73.06 mL, but this difference was not statistically significant (95% CI −225.18 to 79.06; $p = 0.35$; $I^2 = 98\%$). Radiation exposure was significantly reduced with robotic assistance, showing a large effect size favoring robotics (SMD −1.63; 95% CI −2.55 to −0.71; $p = 0.0005$), despite substantial heterogeneity ($I^2 = 93\%$). Conclusion: Robotic-assisted pedicle screw placement provides superior screw accuracy and significantly reduces radiation exposure compared with fluoroscopy-guided techniques. However, evidence for reduced blood loss remains inconclusive. Further prospective studies are required to confirm clinical benefits and long-term outcomes.
Keywords: *Robotic-assisted surgery; fluoroscopy-guided surgery; pedicle screw; lumbar degenerative disease; screw accuracy; radiation exposure and meta-analysis.*

I. INTRODUCTION

Pedicle screw fixation remains a fundamental technique in spine surgery because it provides essential biomechanical stability across a wide range of spinal pathologies, including trauma, deformity, and degenerative disease (Jing et al., 2019). In lumbar degenerative disease, accurate screw placement is particularly important to achieve stable fixation, maintain spinal alignment, and minimize approach-related morbidity.

Conventional pedicle screw placement is commonly performed using freehand or fluoroscopy-guided techniques; however, these approaches are associated with important limitations, including screw malposition, cortical breach, facet joint violation, neurovascular injury, and radiation exposure to both patients and operating-room personnel (Sielatycki et al., 2021). These limitations have encouraged the development and adoption of image-guided and robot-assisted technologies aimed at improving the safety, reproducibility, and precision of spinal instrumentation.

In recent years, robot-assisted spinal instrumentation has emerged as a technological advancement intended to improve preoperative planning, optimize screw trajectory, and enhance intraoperative precision. By integrating robotic guidance with navigation modalities such as CT-based imaging, O-arm navigation, or intraoperative CT, these systems may offer particular advantages in anatomically complex cases and minimally invasive procedures (Wang et al., 2023). Across degenerative lumbar disease, thoracolumbar fractures, and spinal deformity, robotic platforms have increasingly been investigated as alternatives or adjuncts to conventional fluoroscopy-guided methods, although reported benefits vary according to robotic platform, imaging workflow, surgeon experience, and institutional resources (Chang et al., 2024).

Current evidence suggests that robot-assisted pedicle screw placement may provide superior radiographic accuracy compared with fluoroscopy-guided or freehand techniques. Several systematic reviews, meta-analyses, and comparative studies have reported improved Gertzbein–Robbins grades, fewer malpositioned screws, and reduced cortical breach rates with robot-assisted placement across thoracic, thoracolumbar, and lumbar regions (Li et al., 2022). In addition, robot-assisted techniques have been associated with lower rates of facet joint violation in some studies, which may reflect improved trajectory control and more consistent screw alignment (Hou et al., 2022). Some reports also describe reduced revision rates related to screw malposition, although these findings are not uniform across all study designs and clinical settings (Seif et al., 2025).

II. METHODOLOGY

Relevant retrospective cohort studies and retrospective studies evaluating pedicle screw implantation with robotic assistance and fluoroscopy were identified through searches of PubMed and ScienceDirect. The search covered studies published from 2022 to 2025, using the following keywords: fluoroscopy, robotic assistance, spine, and pedicle screw.

Inclusion and exclusion criteria

The inclusion criteria for this study were retrospective cohort studies or retrospective studies involving patients who underwent spinal surgery with pedicle screw placement. Eligible studies had to compare robotic-assisted pedicle screw insertion with fluoroscopy-guided or conventional fluoroscopy-assisted pedicle screw placement and report at least one relevant outcome, such as screw placement accuracy, operative time, blood loss, radiation exposure, complications, or length of hospital stay. Studies involving spinal conditions requiring pedicle screw instrumentation, including degenerative disease, trauma, or other spinal pathologies, were also considered for inclusion. The exclusion criteria were duplicate publications, studies with unavailable full text, studies with incomplete or insufficient outcome data, non-comparative studies, case reports, case series, reviews, editorials, conference abstracts, and studies not relevant to the research question.

Statistical analysis

Meta-analysis was conducted using Review Manager (RevMan) version 5.3 software. For continuous variables, pooled effect estimates were calculated using the mean difference (MD) with 95% confidence intervals (CIs) when outcomes were reported using the same unit of measurement across studies. When continuous outcomes were assessed using different measurement scales, the standardized mean difference (SMD) with 95% CIs was used. For dichotomous variables, pooled estimates were expressed as odds ratios (ORs) with 95% CIs. Statistical heterogeneity among the included studies was assessed using the Chi-square test and quantified with the I^2 statistic. A fixed-effect model was used when heterogeneity was considered low ($P > 0.10$ and $I^2 \leq 50\%$), whereas a random-effects model was applied when significant heterogeneity was present ($P < 0.10$ and $I^2 > 50\%$). In the present meta-analysis, a random-effects model was applied to outcomes demonstrating substantial heterogeneity, including intraoperative blood loss, radiation exposure, and other pooled comparative outcomes. Statistical significance for the overall effect was defined as a P value < 0.05. Publication bias was planned to be assessed by visual inspection of funnel plots. However, given the relatively small number of included studies, the interpretation of funnel plot asymmetry was considered limited.

Risk of Bias Assessment

The methodological quality of the included non-randomized studies was assessed using the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool, which evaluates seven domains of bias: confounding, participant selection, classification of interventions, deviations from intended interventions, missing data, outcome measurement, and selection of the reported result. An overall risk of bias judgment was assigned for each study according to the ROBINS-I guidance.

III. RESULTS AND DISCUSSIONS

Study selection and identification

A systematic literature search was conducted in accordance with the PRISMA 2020 guidelines, and the study selection process is summarized in the PRISMA flow diagram **Figure 1**. A total of 845 records were identified through database searching, comprising 343 records from PubMed and 502 from ScienceDirect. After removal of 25 duplicate records, 820 records remained and were screened based on titles and abstracts, resulting in the exclusion of 800 records that did not meet the eligibility criteria. Twenty full-text articles were sought for retrieval, however 12 reports could not be retrieved. The remaining eight full-text articles were assessed for eligibility, of which three were excluded due to inappropriate study outcomes. Ultimately, 5 studies fulfilled all inclusion criteria and were included in the final review.

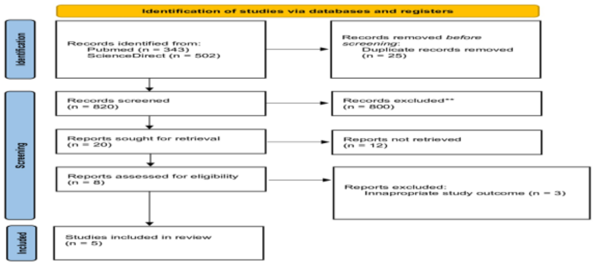


Fig. 1. PRISMA Flowchart

Risk of Bias Assessment

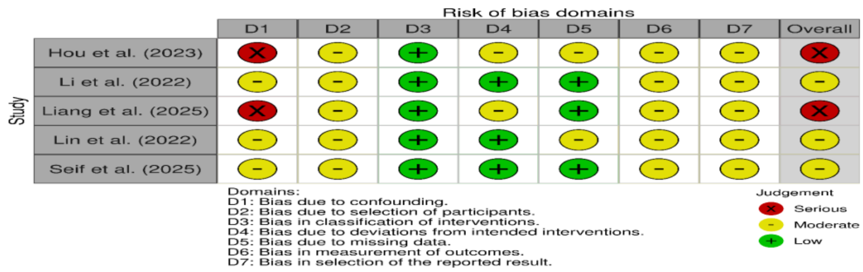


Fig. 2. Risk of Bias Assessment of the Included Studies Using the ROBINS-I Tool

The methodological quality of the included studies was assessed using the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool, evaluating seven domains of bias: confounding, participant selection, intervention classification, deviations from intended interventions, missing data, outcome measurement, and selection of the reported result figure 2. Overall, two studies (Hou et al., 2023 and Liang et al., 2025) were judged to have a serious risk of bias, primarily due to bias from confounding, while the remaining three studies (Li et al., 2022; Lin et al., 2022; and Seif et al., 2025) were considered to have a moderate risk of bias.

Across all included studies, the risk of bias was consistently low for the classification of interventions, reflecting the clear distinction between robotic-assisted and fluoroscopy-guided procedures. Most studies demonstrated low to moderate risk related to deviations from intended interventions and missing data, whereas moderate risk was identified for participant selection, outcome measurement, and selective reporting due to the retrospective study designs, lack of assessor blinding, and absence of prespecified analysis protocols. Overall, the evidence is limited mainly by the observational nature of the included studies and the potential for residual confounding, although the consistency of findings across studies supports the reliability of the pooled estimates.

Summaries of the Included Studies

The five included studies, all of which employed retrospective or retrospective cohort designs, were published between 2022 and 2025 and collectively evaluated 710 patients undergoing pedicle screw placement using either robot-assisted or conventional fluoroscopy-guided techniques. The studies varied in sample size, ranging from 81 to 224 patients, and encompassed diverse patient populations, including adult degenerative spinal conditions and younger cohorts undergoing deformity correction. Across all studies, robot-assisted pedicle screw placement was directly compared with fluoroscopy-assisted techniques, with screw placement accuracy serving as the primary outcome of interest. Accuracy was predominantly assessed using standardized grading systems, most commonly the Gertzbein–Robbins classification, allowing for consistent evaluation across studies.

In addition to accuracy, the included studies reported a broad range of secondary outcomes reflecting both intraoperative performance and postoperative clinical effectiveness. These outcomes included operative or screw placement time, intraoperative blood loss, radiation exposure to patients and surgical staff, length of hospital stay, postoperative pain as measured by the visual analog scale (VAS), functional outcomes such as Macnab scores, and radiographic parameters including Cobb angle correction and facet joint violation. Follow-up duration ranged from short-term perioperative assessment to a minimum of two years in one study, enabling evaluation of both immediate technical outcomes and mid-term clinical or radiographic results. Collectively, these studies provide a detailed and multidimensional comparison of robot-assisted versus fluoroscopy-guided pedicle screw placement, addressing technical precision, surgical efficiency, safety, and clinical outcomes.

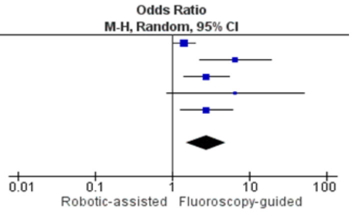
Pedicle Screw Accuracy (per screw accuracy)

Based on the five studies included in this meta-analysis, encompassing 1,937 pedicle screws placed with robotic assistance and 2,497 screws placed under fluoroscopy guidance, robotic-assisted techniques demonstrated significantly superior pedicle screw accuracy. The pooled random-effects analysis yielded an odds ratio (OR) of 2.73 (95% CI 1.50–4.97), indicating that robotic-assisted screw placement was 2.7 times more likely to achieve accurate positioning compared with fluoroscopy-guided methods. This effect was statistically significant ($Z = 3.27$, $p = 0.001$). Moderate-to-substantial heterogeneity was observed across the five studies ($I^2 = 66\%$, χ^2 $p = 0.02$), suggesting variability in study populations, robotic platforms, surgical techniques, or accuracy grading systems. Nonetheless, all studies consistently favored robotic assistance, supporting its overall clinical advantage in enhancing pedicle screw placement accuracy, despite inter-study variability.

Table 1. Forest plot showing pedicle screw accuracy comparing robotic-assisted versus fluoroscopy-guided techniques across five studies

	Robotic-assisted		Fluoroscopy-guided			Odds Ratio
Study or Subgroup	Events	Total	Events	Total	Weight	M-H, Random, 95% CI
Hou et al (2022)	584	647	670	771	31.0%	1.40 [1.00, 1.95]
Liang et al (2025)	242	246	244	270	16.5%	6.45 [2.22, 18.75]
Li et al (2022)	160	172	169	204	23.6%	2.76 [1.38, 5.51]
Lin et al (2022)	363	364	670	682	6.9%	6.50 [0.84, 50.20]
Seif et al (2025)	499	508	543	570	22.0%	2.76 [1.28, 5.92]
Total (95% CI)		**1937**		**2497**	**100.0%**	**2.73 [1.50, 4.97]**
Total events	1848		2296			

Heterogeneity: Tau² = 0.27; Chi² = 11.91, df = 4 (P = 0.02); I² = 66%
Test for overall effect: Z = 3.27 (P = 0.001)



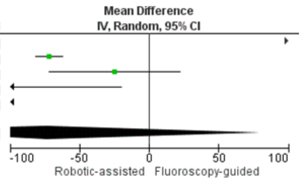
Blood Loss

This meta-analysis of five studies comparing intraoperative blood loss between robotic-assisted and fluoroscopy-guided techniques found no statistically significant difference between the two approaches. Using a random-effects model, the pooled mean difference (MD) was −73.06 mL favoring robotic assistance, but the 95% confidence interval (CI) crossed the null (−225.18 to 79.06 mL), and the overall effect was not significant ($Z = 0.94$, $p = 0.35$). There was considerable heterogeneity among the included studies ($I^2 = 98\%$, χ^2 $p < 0.00001$), indicating substantial variability likely attributable to differences in surgical complexity, case mix, operative levels, surgeon experience, and perioperative blood management protocols. These findings suggest that, despite a trend toward reduced blood loss with robotic assistance, current evidence does not support a clear blood loss advantage over fluoroscopy-guided techniques, and results should be interpreted cautiously given the extreme inter-study heterogeneity.

Table 2. Forest plot showing comparison of intraoperative blood loss between robotic-assisted and fluoroscopy-guided techniques

	Robotic-assisted			Fluoroscopy-guided				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Hou et al (2022)	1,063.07	200.04	45	804.56	137.17	56	19.9%	258.51 [189.90, 327.12]
Liang et al (2025)	66.25	17.5	41	138.2	26.8	45	20.7%	-71.95 [-81.44, -62.46]
Li et al (2022)	248.65	97.53	37	273.41	118.2	44	20.3%	-24.76 [-71.74, 22.22]
Lin et al (2022)	313.7	214.1	75	431.6	529.8	149	19.1%	-117.90 [-215.80, -20.00]
Seif et al (2025)	156.43	102.22	105	563.72	280.48	113	20.1%	-407.29 [-462.58, -352.00]
Total (95% CI)			**303**			**407**	**100.0%**	**-73.06 [-225.18, 79.06]**

Heterogeneity: Tau² = 29118.51; Chi² = 235.01, df = 4 (P < 0.00001); I² = 98%
Test for overall effect: Z = 0.94 (P = 0.35)



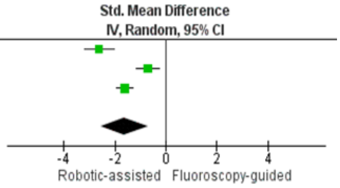
Radiation Exposure

This meta-analysis of three studies comparing radiation exposure between robotic-assisted and fluoroscopy-guided techniques demonstrated a significant reduction in radiation exposure with robotic assistance. Using a random-effects model, the pooled effect showed a standardized mean difference (SMD) of −1.63 (95% CI −2.55 to −0.71), indicating a large effect size favoring robotic-assisted surgery. The overall effect was statistically significant ($Z = 3.46$, $p = 0.0005$). However, substantial heterogeneity was observed ($I^2 = 93\%$, χ^2 $p < 0.00001$), reflecting considerable variability across studies, potentially due to differences in radiation measurement methods, operative techniques, surgeon experience, and case complexity. Despite this heterogeneity, the consistent direction and magnitude of effect suggest that robotic-assisted techniques meaningfully reduce radiation exposure compared with fluoroscopy-guided approaches, which has important implications for improving occupational safety for surgical teams and reducing cumulative radiation risk for patients.

Table 3. Forest plot showing comparison of radiation exposure between robotic-assisted and fluoroscopy-guided techniques

	Robotic-assisted			Fluoroscopy-guided				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Liang et al (2025)	165.53	40.62	41	348.83	87.34	45	31.7%	-2.63 [-3.21, -2.04]
Li et al (2022)	22.2	6	37	25.8	4.2	44	33.4%	-0.70 [-1.15, -0.25]
Seif et al (2025)	109.27	45.01	105	239.88	103.17	113	34.9%	-1.62 [-1.92, -1.31]
Total (95% CI)			**183**			**202**	**100.0%**	**-1.63 [-2.55, -0.71]**

Heterogeneity: $Tau^2 = 0.61$; $Chi^2 = 26.91$, $df = 2$ ($P < 0.00001$); $I^2 = 93\%$
Test for overall effect: $Z = 3.46$ ($P = 0.0005$)



IV. DISCUSSION

This systematic review and meta-analysis was conducted to evaluate the comparative efficacy and safety of robotic-assisted versus fluoroscopy-guided pedicle screw placement in patients with lumbar degenerative disease. Lumbar degenerative disease remains one of the most common causes of chronic low back pain, radiculopathy, neurogenic claudication, and functional limitation, frequently necessitating surgical decompression and instrumented fusion when conservative treatment fails. In this context, the accuracy of pedicle screw placement is of paramount importance, as suboptimal screw positioning may result in pedicle breach, superior facet joint violation, neurological injury, construct instability, and the need for revision surgery. The present review demonstrates that robotic-assisted pedicle screw placement is generally associated with superior screw accuracy and reduced radiation exposure compared with fluoroscopy-guided techniques. In addition, several included studies reported favorable perioperative outcomes with robotic assistance, including lower blood loss, reduced facet joint violation, and shorter hospitalization, although the magnitude and consistency of these benefits varied across studies (Li et al., 2022). Robotic guidance therefore appears to provide meaningful technical advantages in the surgical treatment of lumbar degenerative disease, particularly in procedures where precision is a critical determinant of outcome (Seif et al., 2025).

The findings of the present review are consistent with the growing body of literature suggesting that robotic spinal instrumentation improves the precision and reproducibility of pedicle screw insertion. From a theoretical standpoint, robotic systems provide a more controlled and standardized approach to trajectory planning than conventional fluoroscopy-guided techniques, thereby reducing reliance on surgeon-dependent freehand judgment and repeated intraoperative imaging. This is particularly relevant in minimally invasive lumbar procedures, in which limited exposure and constrained operative corridors may increase the technical difficulty of conventional screw placement (Lin et al., 2022). Prior comparative studies have similarly reported higher rates of optimal screw placement and lower rates of pedicle breach with robotic assistance than with traditional fluoroscopy-guided methods (Hou et al., 2022). Nevertheless, the advantages of robotic systems should be interpreted alongside their practical limitations, including increased capital cost, setup requirements, workflow complexity, and an initial learning curve that may offset perioperative efficiency during early implementation (Hou et al., 2022). Accordingly, while robotic assistance appears to enhance technical performance, fluoroscopy-guided screw placement may still remain a viable and effective option in selected cases when performed by experienced surgeons (Seif et al., 2025).

The effectiveness of robotic-assisted pedicle screw placement can be explained by its underlying mechanism, which integrates three-dimensional imaging, computer-based preoperative or intraoperative trajectory planning, real-time tracking, and robotic arm guidance to facilitate highly accurate instrument navigation. This process enables the surgeon to identify the optimal entry point, angulation, and screw trajectory with greater consistency than is possible with fluoroscopy-guided placement alone. In lumbar degenerative disease, where anatomical distortion, facet hypertrophy, degenerative remodeling, and the technical demands of minimally invasive approaches may complicate pedicle access, this enhanced precision is particularly advantageous (Li et al., 2022). By minimizing repeated manual adjustments and reducing the need for multiple fluoroscopic confirmations, robotic guidance may also contribute to lower radiation exposure and less soft tissue disruption during surgery (Lin et al., 2022). However, robotic-assisted surgery is not devoid of limitations or potential adverse consequences. Technical errors related to image registration, tracker displacement, or system workflow may occur, and operative duration may be prolonged during the early phase of adoption, particularly among teams with limited prior experience (Hou et al., 2022). Although major postoperative complications do not appear to be increased with robotic assistance, these procedural and logistical factors remain important considerations in routine clinical practice (Seif et al., 2025).

Another noteworthy observation from this review is that the potential value of robotic assistance may extend beyond screw accuracy alone. Several studies suggested that robotic guidance may reduce superior facet joint violation, a finding of particular clinical relevance because facet injury has been implicated in accelerated adjacent segment degeneration and poorer postoperative spinal biomechanics (Li et al., 2022). Furthermore, some evidence indicates that the benefit of robotic systems may be more pronounced in technically demanding cases, including multilevel fixation, cortical bone trajectory screw insertion, and minimally invasive fusion procedures, where conventional fluoroscopy-guided methods are inherently more susceptible to trajectory deviation and technical error (Lin et al., 2022). These findings imply that robotic technology may be especially beneficial when maximal precision is required rather than uniformly advantageous across all lumbar instrumentation procedures (Seif et al., 2025). From a clinical standpoint, the present findings support the incorporation of robotic-assisted pedicle screw placement as a valuable adjunct in selected patients with lumbar degenerative disease, particularly when the goals of surgery include optimization of screw accuracy, minimization of radiation exposure, and reduction of procedure-related technical complications (Li et al., 2022).

The studies included in this review provide important insight into the evolving role of robotic assistance in lumbar spinal fixation, yet several methodological limitations must be acknowledged. Most of the included studies were retrospective and single-center in design, which increases the possibility of selection bias, confounding, and limited external validity. In addition, considerable heterogeneity was observed across studies with respect to robotic platforms, surgical indications, operative techniques, accuracy grading systems, and perioperative outcome definitions, thereby limiting the uniformity of pooled interpretation (Seif et al., 2025). Another important limitation is that not all included studies were restricted exclusively to lumbar degenerative disease, as some investigated scoliosis or thoracolumbar fracture populations, which may reduce the direct applicability of their findings to the degenerative lumbar population of interest (Hou et al., 2022; Liang et al., 2025). Nonetheless, the included evidence consistently supports the technical superiority of robotic-assisted screw placement in terms of radiographic accuracy and radiation reduction, even though the effect on broader clinical outcomes remains less definitive (Lin et al., 2022). Therefore, future multicenter prospective studies and randomized controlled trials with standardized definitions, longer follow-up, and formal cost-effectiveness analyses are still required to determine the full clinical value and generalizability of robotic-assisted pedicle screw placement in lumbar degenerative disease (Liang et al., 2025).

V. CONCLUSION

This systematic review and meta-analysis, which included five retrospective studies comparing robot-assisted and conventional fluoroscopy-guided pedicle screw placement, suggests that robot-assisted techniques achieve greater screw placement accuracy than fluoroscopy-guided methods. Robot-assisted placement also appears to reduce facet joint violation and may offer advantages in several perioperative and postoperative outcomes. Nevertheless, no consistent superiority was observed across all secondary outcomes, and the overall evidence remains limited by the retrospective design and heterogeneity of the included studies. Further high-quality prospective research is needed to confirm these findings and clarify the long-term clinical value of robotic assistance in lumbar degenerative disease.

REFERENCES

[1] Chang, H.-K., et al. (2024). Comparison between robot-assisted and navigation-guided minimally invasive transforaminal lumbar interbody fusion: A multicenter study. Neurosurgical Focus, 57(6), E12. https://doi.org/10.3171/2024.9.focus24521

[2] Hou, C., Yang, H., Chen, Y., Yang, Y., Zhang, B., Chen, K., Li, M., Yang, M., & Chen, K. (2023). Comparison of robot versus fluoroscopy-assisted pedicle screw instrumentation in adolescent idiopathic scoliosis surgery: A retrospective study. Frontiers in Surgery, 9. https://doi.org/10.3389/fsurg.2022.1085580

[3] Jing, L., et al. (2019). Accuracy of pedicle screw placement in the thoracic and lumbosacral spines using O-arm-based navigation versus conventional freehand technique. ***Chinese Neurosurgical Journal***, 5(1). https://doi.org/10.1186/s41016-019-0154-y

[4] Li, Y., Chen, L., Liu, Y., Ding, H., Lu, H., Pan, A., Zhang, X., Hai, Y., & Guan, L. (2022). Accuracy and safety of robot-assisted cortical bone trajectory screw placement: A comparison of robot-assisted technique with fluoroscopy-assisted approach. BMC Musculoskeletal Disorders, 23(1). https://doi.org/10.1186/s12891-022-05206-y

[4] Liang, L., Zhao, C., Luo, L., Liu, L., Li, P., Gao, Y., & Zhou, Q. (2025). A comparative study of robot-assisted navigation versus C-arm fluoroscopy in percutaneous pedicle screw fixation for the treatment of thoracolumbar fractures. Scientific Reports, 15(1), 27214. https://doi.org/10.1038/s41598-025-12549-8

[5] Lin, M.-C., Liu, H.-W., Su, Y.-K., Lo, W.-L., & Lin, C.-M. (2022). Robot-guided versus freehand fluoroscopy-guided minimally invasive transforaminal lumbar interbody fusion: A single-institution, observational, case-control study. Neurosurgical Focus, 52(1), E9. https://doi.org/10.3171/2021.10.FOCUS21514

[6] Seif, H., Maragno, E., Gallus, M., Szeöke, S., & Schwake, M. (2025). A retrospective cohort study comparing robot-assisted and conventional fluoroscopy-guided pedicle screw placement. ***Journal of Clinical Medicine***, 14(19), 6831. https://doi.org/10.3390/jcm14196831

[7] Sielatycki, J. A., Mitchell, K., Leung, E., & Lehman, R. A. (2022). State of the art review of new technologies in spine deformity surgery: Robotics and navigation. Spine Deformity, 10(1), 5–17. https://doi.org/10.1007/s43390-021-00403-6

[8] Wang, J., et al. (2023). Spine surgical robotics: Current status and recent clinical applications. Neurospine, 20(4), 1256–1271. https://doi.org/10.14245/ns.2346610.305.