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RESEARCH

Level-specific accuracy of robotic-assisted versus fluoroscopy-assisted lumbar pedicle screw placement: a retrospective comparative cohort study

F. Iaccarino[1] · D. E. Dugoni[4] · G. Pavesi[1,2,3] · A. Landi[4] · M. Gallieni[5] · A. K. Aftahy[5] · C. Iaccarino[1,2,3] · M. Giordano[5]

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Abstract

Background robotic-assisted (RA) pedicle screw placement has been increasingly adopted in lumbar spine surgery because of its potential to improve accuracy compared with conventional fluoroscopy-assisted (FA) techniques. However, vertebral level-specific differences remain insufficiently characterized. This study compared RA and FA lumbar pedicle screw placement focusing on level-specific and side-specific radiographic accuracy. *Methods* a retrospective single-center comparative cohort study was conducted using prospectively collected data. A total of 2065 lumbar pedicle screws were analyzed, including 1053 placed using RA and 1012 using conventional FA instrumentation. Screw accuracy was assessed postoperatively using the Gertzbein-Robbins classification, with Grade A considered optimal. Level-specific and side-specific analyses were performed for L1-L5. Fisher's exact test, clustered logistic regression, and propensity score weighted sensitivity analyses were used for statistical comparisons. *Results* Grade A placement was achieved in 99.1% of RA screws (1044/1053) versus 87.9% of FA screws (890/1012) ($p<0.001$). Robotic-assisted instrumentation demonstrated significantly higher rates of optimal screw placement across all lumbar levels and both sides. The greatest relative differences were observed at upper lumbar levels, particularly L1-L2. At L5, Grade A placement reached 100.0% on the right side and 99.5% on the left side in the RA cohort, compared with 89.2% and 88.1% in the FA cohort (both $p<0.001$). Fluoroscopy-assisted instrumentation independently predicted lower odds of optimal screw placement (OR 0.042, 95% CI 0.016–0.111; $p<0.001$). *Conclusions* robotic-assisted lumbar pedicle screw placement was associated with significantly higher radiographic Grade A screw placement accuracy than FA instrumentation.

Keywords Robotic spine surgery · Pedicle screw · Robotic-assisted surgery · Lumbar spine · Screw accuracy · Spinal navigation · Fluoroscopy-assisted technique.

Introduction

Pedicle screw fixation represents the standard technique for posterior lumbar stabilization and is widely used in the treatment of degenerative, traumatic and deformity-related spinal disorders. Accurate pedicle screw placement is essential to ensure biomechanical stability while minimizing complications such as cortical breaches, neurological injury, vascular damage, suboptimal fixation and revision surgery [1]. Conventional FA pedicle screw placement relies primarily on anatomical landmarks and fluoroscopic guidance. Although satisfactory outcomes can be achieved in experienced hands, screw placement accuracy may be affected by anatomical variability, spinal deformity, limited intraoperative visualization and surgeon-dependent

✉ F. Iaccarino
federico.iacca1995@gmail.com

1 School of Neurosurgery, Department of Biomedical, Metabolic and Neural Sciences, University of Modena and Reggio Emilia, Modena, Italy

2 Department of Neurosurgery, University Hospital of Modena, Modena, Italy

3 Neurosurgery Unit, AUSL RE IRCCS, Reggio Emilia, Italy

4 Neurosurgery unit, Centro Chirurgico Toscano, Arezzo, Italy

5 Neurosurgery unit, International Neuroscience Institute, Hannover, Germany

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technical variability [2]. Furthermore, repeated fluoroscopic imaging may increase radiation exposure for both patients and surgical staff [3, 4]. Over the past decade, robotic-assisted (RA) spinal surgery has emerged as an increasingly adopted technology aimed at improving the precision and reproducibility of pedicle screw instrumentation. Robotic systems integrate intraoperative or preoperative imaging with computer-assisted trajectory planning and navigated guidance, potentially improving screw placement accuracy while reducing technical variability associated with conventional instrumentation techniques [5, 6]. Several systematic reviews and meta-analyses have demonstrated superior screw placement accuracy using RA and navigated techniques compared with conventional FA instrumentation [7–13]. Despite growing evidence supporting robotic guidance, most available studies primarily report overall screw placement accuracy, whereas relatively limited evidence is available regarding level-specific performance across the lumbar spine. This aspect may be clinically relevant because pedicle morphology and technical complexity vary considerably according to vertebral level. Upper lumbar pedicles are generally smaller and more medially angulated, whereas lower lumbar levels, particularly L4 and L5, require highly convergent trajectories and present more complex anatomical constraints [14, 15]. Consequently, the potential advantages of robotic guidance may vary across lumbar segments. The aim of the present study was therefore to compare RA and conventional FA lumbar pedicle screw placement in a large retrospective cohort, with particular focus on vertebral level-specific and side-specific radiographic accuracy using the Gertzbein-Robbins classification system.

Methods

Study design and patient population

A retrospective comparative cohort study was conducted at a single tertiary referral spine center (Centro Chirurgico Toscano, Arezzo, Italy) using prospectively collected surgical data. A total of 219 patients were initially scheduled to undergo RA posterior lumbar fusion using the Medtronic Mazor X system (Mazor Robotics Ltd., Caesarea, Israel) between January 2021 and April 2026. In three cases, robotic guidance was abandoned because of workflow-related issues and instrumentation was completed using conventional FA techniques. Therefore, 216 completed RA procedures were included in the final robotic accuracy analysis. A control cohort of 216 patients underwent conventional FA instrumentation before the introduction of robotic technology at our institution between January 2016 and December 2020. Because the FA cohort was treated before the implementation of robotic technology at our institution, the study design inherently reflects a sequential cohort structure. Consequently, temporal bias cannot be excluded, including potential changes in perioperative workflow, imaging protocols, implant technology, patient selection criteria, and cumulative surgical experience over time. To mitigate this limitation, all procedures were performed at the same institution by the same surgical team (two attending surgeons), and postoperative screw assessment was conducted using a standardized CT-based protocol. The RA cohort represents the institution's early adoption phase of robotic instrumentation; however, surgeon-specific learning curve effects were not formally evaluated. The surgical indication for degenerative spinal pathology was based on the results of both flexion-extension X-rays and magnetic resonance imaging (MRI), which confirmed the presence of instability in the segments under consideration. This was in the context of clinical symptoms that were unresponsive to conservative treatment for a period longer than six weeks and that interfered with normal daily activities (Oswestry Disability Index > 40%). In cases of traumatic pathology, stabilization was performed for fractures deemed unstable based on their morphology as assessed by computed tomography (CT) and MRI. Patients who underwent lumbar instrumentation using either a RA or a conventional FA technique were included. Only pedicle screws placed from L1 to L5 were analyzed. Postoperative thin-slice CT scans (≤ 1 mm slice thickness) with multiplanar reconstruction were obtained in all patients during the early postoperative period. Cases lacking adequate postoperative imaging for screw trajectory evaluation or incomplete screw grading data were excluded from the analysis. The final study population consisted of 432 patients and 2065 lumbar pedicle screws, including 1053 screws inserted using robotic assistance and 1012 screws inserted using the conventional FA technique. The study was conducted in accordance with the Declaration of Helsinki and the STROBE guidelines for observational studies. Ethical approval was obtained from the Institutional Review Board of Centro Chirurgico Toscano (Arezzo, Italy) in accordance with local institutional requirements.

Surgical techniques

Robotic-assisted technique

In the RA cohort, surgery was performed using the Medtronic Mazor X robotic guidance platform (Mazor Robotics Ltd., Caesarea, Israel). After induction of general anesthesia, patients were positioned prone and the robotic platform was attached to the operating table. A reference array was secured to the posterior superior iliac spine or to the spinous process according to the surgical approach.

Intraoperative three-dimensional imaging was then acquired and automatically registered with the robotic navigation system. Following registration verification, pedicle screw trajectories were planned on the robotic workstation according to patient-specific anatomy. The robotic arm guided the trajectory for each pedicle screw, allowing navigated drilling, pedicle cannulation and screw insertion under real-time guidance. Final fluoroscopic verification was performed when required. Robotic workflow-related events were prospectively recorded, including registration failures, intraoperative conversion to conventional FA instrumentation, robotic abandonment, screw repositioning after guidance, and device-related technical complications.

Fluoroscopy-assisted technique

In the conventional FA cohort, pedicle screws were inserted using standard posterior anatomical landmarks combined with fluoroscopic guidance. Following posterior exposure of the lumbar spine, the pedicle entry point was identified at the junction of the pars interarticularis, transverse process and superior articular process. Pedicle cannulation was performed using a pedicle probe under anteroposterior and lateral fluoroscopic control. Pedicle wall integrity was assessed intraoperatively using a ball-tipped probe before tapping and screw insertion. Final screw positioning was confirmed using fluoroscopic imaging.

Radiographic assessment

Postoperative screw positioning was evaluated using postoperative CT imaging. Screw accuracy was graded according to the Gertzbein–Robbins classification system (Grade A - screw is completely within the pedicle; Grade B - pedicle cortical breach <2 mm; Grade C - pedicle cortical breach ≥ 2 mm and <4 mm; Grade D - pedicle cortical breach ≥ 4 mm and <6 mm; Grade E - pedicle cortical breach ≥ 6 mm). Grade A screws were considered optimal placements. Level-specific and side-specific analyses were performed for all lumbar vertebral levels (L1-L5) bilaterally. Screw grading was independently performed by two observers blinded to surgical technique. In cases of disagreement, consensus evaluation was obtained. Interobserver agreement was excellent ($\kappa = 0.91$).

Statistical analysis

Descriptive statistics were reported as frequencies and percentages for categorical variables and as mean ± standard deviation for continuous variables. The primary outcome was the proportion of Grade A screw placements. Comparisons between RA and FA techniques were performed using Fisher's exact test. To account for within-patient correlation due to multiple screws per patient, logistic regression with cluster-robust standard errors at the patient level was performed to evaluate factors associated with optimal screw placement (Grade A). Covariates included surgical technique, pathology, vertebral level, screw side and patient age. Odds ratios (ORs) with 95% confidence intervals (CIs) were calculated. All statistical analyses were performed using Python (version 3.x) with the pandas, NumPy, SciPy and statsmodels libraries. A two-tailed p-value <0.05 was considered statistically significant. Given the baseline imbalance in surgical approach and pathology distribution between cohorts, an inverse probability of treatment weighting (IPTW) sensitivity analysis based on propensity scores was performed. Propensity scores were estimated using logistic regression including surgical approach, pathology, and patient age. Stabilized IPTW weights were then applied to screw-level analyses. A weighted generalized estimating equation model with clustering at the patient level was used to evaluate the association between surgical technique and Grade A screw placement.

Results

Patient population and baseline characteristics

A total of 432 patients undergoing lumbar pedicle screw fixation were included in the study, comprising 216 patients treated with RA instrumentation and 216 treated using the conventional FA technique. Overall, 2065 lumbar pedicle screws were analyzed, including 1053 RA screws and 1012 FA screws. Baseline demographic and clinical characteristics are summarized in Table 1. Mean patient age was comparable between groups (60.5 ± 14.2 years in the RA cohort vs. 59.7 ± 13.6 years in the FA cohort; $p = 0.568$). The two cohorts were generally comparable regarding patient-related anatomical and clinical factors influencing pedicle screw placement accuracy. Mean body mass index (BMI) was 27.8 ± 4.6 kg/m². The prevalence of major comorbidities was similar between groups, including hypertension (49%), type 2 diabetes mellitus (17%), osteoporosis (21%), chronic cardiopulmonary disease (14%), and previous lumbar surgery (19%). 32% of patients were current or former smokers. Significant differences were observed regarding surgical approach distribution and underlying pathology. Minimally invasive surgery was more frequently performed in the RA cohort, whereas open procedures predominated in the FA cohort ($p < 0.001$).

Table 1 Demographics and clinical characteristics

Characteristic	RA ($N=216$)	FA ($N=216$)	Total ($N=432$)	p-value
Mean Age (years ± SD)	60.5 ± 14.2	59.7 ± 13.6	60.1 ± 13.9	0.568
Surgical approach				< 0.001
- Open	109 (50.5%)	190 (88.0%)	299 (69.2%)	
- MIS	107 (49.5%)	26 (12.0%)	133 (30.8%)	
Pathology				< 0.001
- Degenerative spondylolisthesis	57 (26.4%)	96 (44.4%)	153 (35.4%)	
- Unstable fracture	9 (4.2%)	5 (2.3%)	14 (3.2%)	
- Isthmic spondylolisthesis	42 (19.4%)	12 (5.6%)	54 (12.5%)	
- Lumbar stenosis	35 (16.2%)	48 (22.2%)	83 (19.2%)	
- Junctional pathology	4 (1.9%)	24 (11.1%)	28 (6.5%)	
- Spinal deformity	33 (15.3%)	7 (3.2%)	40 (9.3%)	
- Degenerative disc disease	36 (16.7%)	24 (11.1%)	60 (13.9%)	

Table 2 Pedicle screw placement outcomes by technique and pathology

Screw-level outcome	RA (N screws = 1053)	FA (N screws = 1012)	Total (N screws = 2065)	p-value
Gertzbein-Robbins grade				< 0.001
- Grade A	1044 (99.1%)	890 (87.9%)	1934 (93.7%)	
- Grade B	9 (0.9%)	115 (11.4%)	124 (6.0%)	
- Grade C	0 (0.0%)	7 (0.7%)	7 (0.3%)	
- Grade A + B	1053 (100%)	1005 (99.3%)		
Optimal placement (Grade A) by pathology				
- Degenerative spondylolisthesis	271 (98.5%)	400 (90.9%)	671 (93.8%)	
- Unstable fracture	40 (100.0%)	15 (62.5%)	55 (85.9%)	
- Isthmic spondylolisthesis	126 (98.4%)	43 (89.6%)	169 (96.0%)	
- Lumbar stenosis	174 (100.0%)	195 (84.8%)	369 (91.3%)	
- Junctional pathology	24 (100.0%)	108 (85.7%)	132 (88.0%)	
- Spinal deformity	272 (98.9%)	38 (82.6%)	310 (96.6%)	
- Degenerative disc disease	137 (100.0%)	91 (92.9%)	228 (97.0%)	

Robotic workflow performance

Among 219 procedures initially planned for RA instrumentation, robotic workflow-related issues leading to abandonment of the robotic platform occurred in 3 cases (1.4%). Instrumentation was successfully completed using conventional FA techniques. Because robotic guidance was not completed, these cases were excluded from the robotic accuracy analysis. No major device-related adverse events were observed. The robotic workflow completion rate was 98.6% (216/219).

Overall screw placement accuracy

Overall radiographic accuracy was significantly higher in the RA cohort compared with the FA cohort (Table 2).

Grade A screw placement was achieved in 1044 of 1053 RA screws (99.1%) compared with 890 of 1012 FA screws (87.9%) ($p < 0.001$). Grade B breaches occurred in 0.9% of RA screws and 11.4% of FA screws, whereas Grade C breaches were observed exclusively in the FA cohort (0.7%). Across all pathological subgroups, RA instrumentation consistently demonstrated numerically higher rates of optimal screw placement compared with the conventional FA technique. Clinically acceptable screw placement (Grade A + B) was achieved in 100% (1053/1053) of RA screws and 99.3% (1005/1012) of FA screws.

Level-specific screw placement accuracy

Detailed vertebral level-specific and side-specific screw accuracy data are summarized in Table 3; Fig. 1. The largest relative differences between techniques were observed at the upper lumbar levels (L1-L2). At L1, Grade A placement was achieved in 96.2% and 100.0% of RA screws on the right and left sides, respectively, compared with 57.1% and 62.5% in the FA cohort. Similarly, at L2, robotic guidance achieved Grade A placement rates of 97.9% on the right side and 100.0% on the left side, whereas FA placement achieved 58.6% and 60.0%, respectively (all $p < 0.05$). At mid-lumbar levels (L3-L4), RA instrumentation continued to demonstrate significantly higher rates of optimal screw placement. At L3, Grade A placement ranged from 97.6% to 100.0% in the RA cohort compared with 89.0% bilaterally in the FA cohort. At L4, RA placement achieved Grade A rates of 98.2% on the right side and 99.4% on the

Table 3 Level-specific and side-specific Grade A screw placement accuracy

Level	Side	FA %	RA %	*n* FA	*n* RA	*p*-value
L1	Right	57.1	96.2	7	26	0.023
L1	Left	62.5	100.0	8	27	0.009
L2	Right	58.6	97.9	29	47	<0.001
L2	Left	60.0	100.0	30	47	<0.001
L3	Right	89.0	100.0	91	85	0.002
L3	Left	89.0	97.6	91	85	0.034
L4	Right	92.9	98.2	183	170	0.020
L4	Left	91.8	99.4	184	171	<0.001
L5	Right	89.2	100.0	195	197	<0.001
L5	Left	88.1	99.5	194	198	<0.001

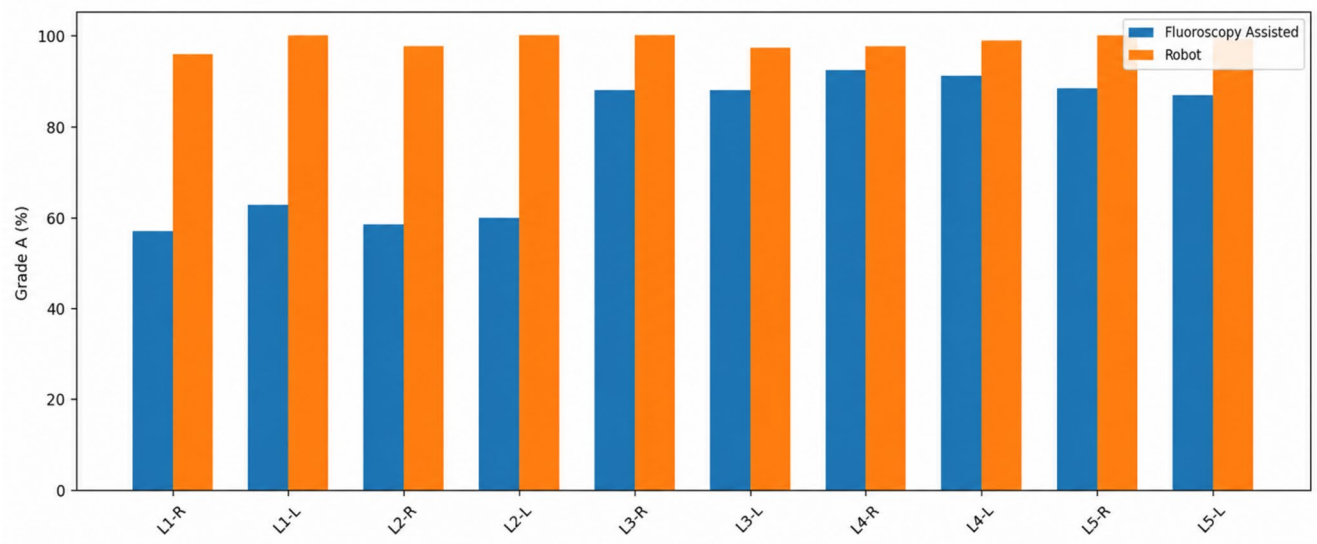

Fig. 1 Level-specific and side-specific rates of Grade A (bars) pedicle screw placement according to the Gertzbein-Robbins classification in the RA and FA cohorts. Exact numerators and denominators are reported in Table 3. Robotic-assisted instrumentation demonstrated consistently higher radiographic accuracy across all lumbar vertebral levels (L1-L5), with the greatest relative differences observed at upper lumbar levels (L1-L2)

left side, compared with 92.9% and 91.8%, respectively, in the FA cohort. At L5, robotic guidance maintained consistently high accuracy. Grade A placement reached 100.0% for right-sided screws and 99.5% for left-sided screws in the RA cohort, compared with 89.2% and 88.1%, respectively, in the FA cohort (both $p<0.001$). Level-specific 95% confidence intervals for Grade A accuracy are reported in Supplementary Table S1.

Logistic regression analysis

Logistic regression with cluster-robust standard errors at the patient level was performed and identified surgical technique as the strongest independent predictor of optimal screw placement (Table 4). Compared with RA instrumentation, the FA technique was associated with significantly lower odds of achieving Grade A screw positioning (OR 0.042, 95% CI 0.016–0.111; $p<0.001$). Among vertebral levels, screws placed at L4 demonstrated significantly higher odds, while L5 showed borderline significance of Grade A positioning compared with L1. Screw side and patient age were not significantly associated with optimal placement accuracy.

Propensity score weighted sensitivity analysis

To address baseline imbalances between cohorts, an IPTW sensitivity analysis was performed. After weighting, surgical approach distribution was substantially improved, with minimally invasive procedures accounting for 31.5% of the RA cohort and 34.0% of the FA cohort. The association between RA instrumentation and higher Grade A screw placement accuracy remained significant after IPTW adjustment. Weighted Grade A accuracy was 99.4% in the RA cohort and 88.6% in the FA cohort. In the weighted GEE model clustered by patient, FA instrumentation remained

Table 4 Clustered logistic regression analysis of predictors of Grade A screw placement

Term	Odds Ratio	95% CI Low	95% CI High	*p*-value
Group (Ref: RA)				
- FA	0.042	0.016	0.111	<0.001
Pathology (Ref: Degenerative spondylolisthesis)				
- Unstable fracture	0.332	0.101	1.093	0.070
- Isthmic spondylolisthesis	0.676	0.297	1.535	0.349
- Lumbar stenosis	0.616	0.326	1.164	0.135
- Junctional pathology	0.853	0.405	1.797	0.676
- Spinal deformity	0.657	0.262	1.644	0.369
- Degenerative disc disease	1.260	0.424	3.742	0.678
Level (Ref: Level 1)				
- Level 2	0.847	0.281	2.553	0.769
- Level 3	3.791	0.924	15.558	0.064
- Level 4	5.108	1.385	18.842	0.014
- Level 5	3.665	1.002	13.401	0.050
Side (Ref: Right side)				
- Left side	0.958	0.662	1.387	0.822
Age	0.994	0.972	1.015	0.560

associated with significantly lower odds of Grade A screw placement compared with RA instrumentation (OR 0.042, 95% CI 0.017–0.103; $p<0.001$).

Discussion

The present study demonstrated that RA lumbar pedicle screw placement was associated with significantly higher radiographic accuracy compared with conventional FA instrumentation across all lumbar levels. Overall, Grade A placement according to the Gertzbein-Robbins classification was achieved in 99.1% of RA screws compared with 87.9% of FA screws. Furthermore, robotic guidance remained consistently associated with superior accuracy in both side-specific and vertebral level-specific analyses. When clinically acceptable placement was defined as Grade A or Grade B according to the Gertzbein-Robbins classification, both techniques demonstrated very high success rates, indicating that the primary difference between cohorts concerned the achievement of optimal (Grade A) rather than acceptable screw positioning. The exceptionally high Grade A placement rate observed in the RA cohort is comparable to the upper range of accuracy values reported in contemporary RA surgery literature. Importantly, the superiority of RA instrumentation remained significant after propensity score weighting for surgical approach, pathology, and age. These findings suggest that the observed difference in Grade A screw placement accuracy was not solely explained by baseline imbalances between cohorts. Nevertheless, residual confounding inherent to the retrospective sequential cohort design cannot be completely excluded. Importantly, the present study extends previous evidence by demonstrating that the magnitude of the robotic advantage is not uniform across lumbar vertebral levels, suggesting that anatomical complexity may modulate the relative benefit of robotic guidance. These findings are consistent with the growing body of literature supporting RA spinal instrumentation. Previous systematic reviews and meta-analyses have consistently reported improved pedicle screw accuracy with RA and navigated techniques compared with conventional FA placement. In particular, *Perdomo-Pantoja et al.* [7] analyzed more than 51,000 pedicle screws and demonstrated significantly improved accuracy using computer-assisted and RA technologies compared with conventional techniques. Similarly, *Matur et al.* [8] reported that RA and navigated pedicle screw placement was both safer and more accurate than conventional FA instrumentation. More recent evidence from *Papalia et al.* [9] further confirmed that navigated thoracolumbar screw fixation is associated not only with higher accuracy but also with improved clinical outcomes. The high degree of precision observed in the present RA cohort further supports the ability of robotic systems to improve trajectory reproducibility and reduce screw malposition. These advantages likely derive from the integration of preoperative or intraoperative imaging, computer-assisted trajectory planning and rigid navigated guidance, which collectively reduce technical variability during screw insertion. An important aspect of the present study is the detailed level-specific evaluation across the lumbar spine. Interestingly, the greatest relative differences between techniques were observed at the upper lumbar levels, particularly L1 and L2. Because upper lumbar pedicles are generally smaller and more medially angulated, they provide narrower anatomical corridors and reduced tolerance for technical error. In these anatomically constrained segments,

robotic trajectory planning and rigid guidance may offer a particular advantage over conventional FA instrumentation. However, the number of screws available for analysis at L1 and L2 was limited, especially in the FA cohort. Therefore, these findings should be interpreted cautiously, as reflected by the wider confidence intervals observed at the upper lumbar levels. Robotic-assisted instrumentation also demonstrated consistently high accuracy at lower lumbar levels, particularly at L5, where Grade A placement approached 100%. Accurate screw insertion at L5 is technically demanding because of convergent pedicle trajectories, variable sacral anatomy and challenging fluoroscopic visualization. Robotic guidance may facilitate trajectory alignment and spatial orientation in these complex anatomical regions, thereby improving reproducibility and reducing the likelihood of cortical breach. The clustered logistic regression analysis further strengthened these findings by demonstrating that the FA technique was independently associated with significantly lower odds of optimal screw placement. This association remained significant after adjustment for pathology, vertebral level, screw side and patient age, supporting the robustness of the observed differences between techniques. The present study was designed to evaluate radiographic accuracy and was not powered to assess clinical outcomes. Therefore, no conclusions regarding neurological complications, symptomatic screw malposition, revision surgery, operative efficiency, radiation exposure, hospital stay, or cost-effectiveness can be drawn from the present data. Nevertheless, improved screw positioning accuracy may potentially reduce the risk of neurovascular injury, instrumentation failure, and revision procedures [16, 17]. In addition, robotic systems may contribute to greater procedural standardization and reduced variability related to surgeon experience [18]. The findings of the present study support the increasing adoption of RA technologies in lumbar spine surgery, particularly in anatomically demanding cases and when high reproducibility is required. However, the clinical and economic impact of RA instrumentation remains an area of ongoing investigation, and future studies evaluating long-term clinical outcomes and cost-effectiveness are warranted. From a technical perspective, robotic guidance may be particularly advantageous in situations characterized by narrow pedicles, severe facet degeneration, rotational deformity or challenging fluoroscopic visualization. The integration of trajectory planning and navigated execution may improve spatial orientation and reduce dependence on repeated fluoroscopic confirmation, potentially contributing to improved procedural reproducibility. While previous meta-analyses have established the overall superiority of RA instrumentation, the specific contribution of the present study lies in the vertebral level-specific and side-specific evaluation of screw accuracy across the lumbar spine.

Limitations

Several limitations should be acknowledged. First, the study was retrospective and conducted at a single institution, introducing the potential for selection bias and limiting generalizability. Second, only radiographic screw placement accuracy was evaluated, whereas clinically relevant outcomes such as neurological complications, fusion rates, operative time, radiation exposure and revision surgery were not assessed. Third, differences in surgical approach distribution and pathology between cohorts may have influenced the observed results despite multivariable adjustment. Fourth, the study did not account for surgeon-specific experience or learning curves, which may affect pedicle screw accuracy. Finally, although screw grading was standardized using the Gertzbein-Robbins classification, some degree of interobserver variability in radiographic assessment cannot be completely excluded. An additional important limitation is the sequential cohort design. The FA cohort was treated before the introduction of robotic technology, whereas the RA cohort was treated later. Therefore, the observed differences may partly reflect temporal changes in surgical practice, perioperative management, imaging quality, implant systems, and accumulated surgeon experience rather than the robotic platform alone. Although all procedures were performed by the same surgical team and analyses were adjusted using multivariable models and IPTW weighting, residual confounding due to measured and unmeasured variables cannot be completely excluded. Furthermore, surgeon-specific learning-curve effects were not formally evaluated and may have influenced the observed accuracy rates. Although robotic workflow-related failures were uncommon, three procedures required abandonment of the robotic platform. Such events may affect the real-world applicability of robotic systems and should be considered when interpreting the overall benefits of the technology. Therefore, caution is warranted when extrapolating these findings to institutions with different surgical workflows, imaging protocols and levels of robotic experience.

Conclusions

In this retrospective comparative cohort study, RA lumbar pedicle screw placement was associated with significantly higher radiographic accuracy compared with conventional FA instrumentation. Grade A screw placement was achieved in 99.1% of RA screws compared with 87.9% of FA screws, with significant advantages favoring robotic

guidance observed across all lumbar vertebral levels and on both sides. The greatest relative differences were identified at anatomically challenging segments, particularly the upper lumbar spine. These findings support the association between robotic assistance and improved radiographic Grade A screw placement accuracy. However, whether this radiographic advantage translates into superior clinical outcomes remains to be determined. Prospective multicenter studies evaluating clinical outcomes, complication rates, radiation exposure and cost-effectiveness are warranted to better define the long-term clinical impact of robotic guidance in spine surgery.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval This study was conducted in accordance with the principles of the Declaration of Helsinki and was reviewed and approved by the Institutional Review Board of Centro Chirurgico Toscano (Arezzo, Italy) in accordance with local institutional requirements.

Informed consent The requirement for informed consent was waived by the Institutional Review Board because of the retrospective observational design and anonymized analysis of routinely collected clinical data.

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