Journal of Robotic Surgery (2025) 19:474
https://doi.org/10.1007/s11701-025-02654-1

RESEARCH

Robotic spine surgery compared with fluoroscopic-assisted surgery: advantages, disadvantages, future perspectives

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

Received: 19 May 2025 / Accepted: 5 August 2025

Abstract

Background Robotic spine surgery (RSS) could potentially overcome some limitations of fluoroscopic-assisted surgery (FAS). The aim of this study was to analyze RSS advantages compared to FAS and the impact of a dedicated nursing team on surgical workflow efficiency.

Materials and methods We retrospectively analyzed 260 adult patients with thoracolumbar degenerative/traumatic instability. One-hundred-thirty underwent posterior fusion with Medtronic Mazor X, while 130 were treated with FAS. Parameters included operative duration, OR entry-to-start time, screw implantation time, accuracy (Gertzbein-Robbins classification), radiation exposure, complications, and Oswestry Disability Index (ODI). We also assessed OR entry-start surgery/implant times, number of screws implanted, and duration of the intervention before and after the introduction of a dedicated nursing team for RSS.

Results RSS reduced implantation times with higher accuracy of pedicle screws. It decreased exposure to radiation for both surgeons and patients. In our case series, there were no significant differences in complications or hospitalization times. A 10% difference in means was observed to the most recent follow-up between ODI of the patients operated with robotic (5%) and fluoroscopic-assisted (15%) surgery. In the RSS group, three (2.3%) cases of junctional syndrome occurred, seventeen (13.1%) with FAS. Implementing a dedicated nursing team reduced OR entry-start time and overall duration of robotic procedures.

Conclusions In our experience, RSS had important advantages compared to FAS in terms of accuracy of pedicle screw positioning. It reduced implantation times and postoperative pain without additional complications. The learning curve of the operating room staff represented a crucial point in the speed of execution of the procedure.

Keywords Robotic spine surgery · Fluoroscopic-assisted surgery · Pedicle screw accuracy · Radiation exposure · Surgical workflow efficiency · Dedicated nursing team

Introduction

Robotic spine surgery (RSS) is a reality that is increasingly spreading throughout the world [1]. This tool could help to overcome some of the limitations of fluoroscopic-assisted surgery (FAS) [2]. Medical robots generally fall into three categories: supervisory-controlled, telesurgical, and shared-control. Supervisory-controlled robots allow the surgeon to plan the operation that they perform under close human supervision. Telesurgical robots allow the surgeon to directly control the robot and its instruments throughout the entire procedure from a remote location. Shared-control robots simultaneously allow both the surgeon and the robot to control instruments and motions [3]. Of course, these new tools should be utilized when traditional surgery is mastered,

✉ 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 International Neuroscience Institute, Hannover, Germany

Published online: 10 August 2025

but at the same time, they imply a unique working method, a learning curve, and different timing during surgery [4]. Another crucial factor is the training of the entire operating room staff in order to carry out the various steps efficiently [5]. Once this tool has been mastered, however, the advantages could be very helpful: accuracy in positioning the pedicle screws, even in cases of complex anatomy or poor bone quality, with consequent reduction in the risk of revision, shorter implant procedures (especially in case of long constructs), less operator fatigue, and exposure to radiation [6–11]. The aim of this study is to analyze the RSS activity compared to FAS regarding timing, complications, accuracy of screw placement, radiation exposure, and clinical outcomes. Moreover, we studied the impact of a dedicated nursing team on surgical workflow efficiency, a variable rarely explored in comparative literature.

Materials and methods

In this single-center retrospective study, two-hundred-sixty adult patients suffering from degenerative or traumatic instability of the thoracolumbar spine were considered. One-hundred-thirty underwent posterior fusion using Medtronic Mazor X (Mazor Robotics Ltd., Caesarea, Israel) in the period 01/01/2021 to 01/06/2024, then we considered a control group of one-hundred-thirty patients that were operated on using fluoroscopic-assisted technique before the introduction of the robot. 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. All the procedures were carried out at Centro Chirurgico Toscano in Arezzo, and the surgeons were the same for both groups. The two patient groups were homogeneous in terms of demographic/clinical characteristics and pathology type. The average body mass index (BMI) was 28.1 ± 4.3 kg/m^2. The prevalence of comorbidities was comparable between the groups: hypertension (47%), type 2 diabetes mellitus (18%), chronic cardiac disease (12%), chronic obstructive pulmonary disease (10%), and diagnosed osteoporosis (22%). Thirty-five percent of patients were current or former smokers, while 15% reported chronic alcohol use. The parameters considered were: sex, age, pathology, surgical technique (open/percutaneous), robotic technique (scan and plan/CT to fluoro), operating room (OR) entry-start surgery time, number of screws, number of cages, duration of the operation, duration of implantation of the screws, accuracy of the screws (Gertzbein-Robbins classification: grade A—screw is completely within the pedicle; grade B—screw breaches the pedicle cortex by < 2 mm; grade C—pedicle cortical breach < 4 mm; grade D—pedicle cortical breach < 6 mm; grade E—pedicle cortical breach > 6 mm), exposure to radiation, revision, infection, hospitalization time, blood transfusion, and junctional pathology. The imaging modality used to assess screw placement accuracy was postoperative CT, evaluated by an independent radiologist. Postoperative radiological follow-up was carried out after one, three, six, and twelve months. Clinical outcomes were assessed by the Oswestry Disability Index (ODI). The minimal clinically important difference (MCID) threshold for ODI is generally accepted to be around 10%. ODI scores of the robotic-assisted and fluoroscopy-guided surgery groups were compared in relation to this threshold to evaluate whether the observed postoperative improvements were clinically meaningful. Data of the two groups were compared using Chi-square tests for categorical variables and independent samples t-tests for continuous variables. We also assessed OR entry-start surgery/implant times, number of screws implanted, and duration of the intervention before and after the introduction of a dedicated nursing team for RSS.

Robotic spine surgery workflow

After general anesthesia induction, the patient is positioned prone and the Mazor X (Mazor Robotics Ltd., Caesarea, Israel) is attached to the surgical bed using a frame adaptor. Sterile draping is set up and the robotic reference star is attached to the robot. A Schanz screw placed with a triton drill with pin collet attachment into the posterior superior iliac spine (PSIS) can be used (other alternatives are a specific bridge or a clamp anchored to the spinous processes for open surgeries) to connect the robotic arm to the patient. After this procedure, any patient movement should be avoided in order to maintain the accuracy. A sterile towel is placed over the surgical site and a 3Define Scan is performed to make the robot's camera reconstruct the operating field space (Fig. 1). The snapshot tracker, which is the robotic arm reference, is then attached to the surgical arm. A snapshot step is performed positioning the navigation camera where it can visualize both the snapshot tracker and the reference frame. This process saves these relative positions and relates them to the robotic system allowing the navigation to display instruments in relation to the three-dimensional (3D) map of the robotic system. The snapshot tracker is then removed and replaced with a radiopaque marker (StarMarker, Fig. 2). The following robotic registration creates a 3D map of the robotic system and the patient anatomy as it is positioned on the OR table. This is accomplished by taking

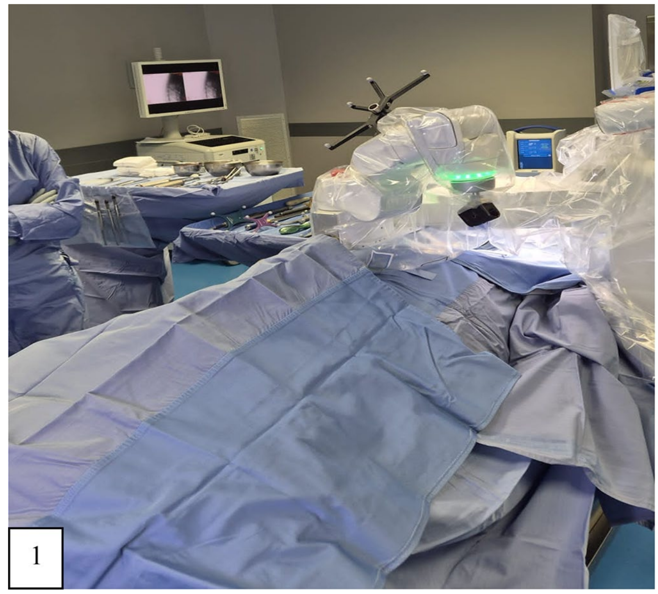


Fig. 1 Sterile draping and preparation for 3Define Scan with the reference star already attached to the robot

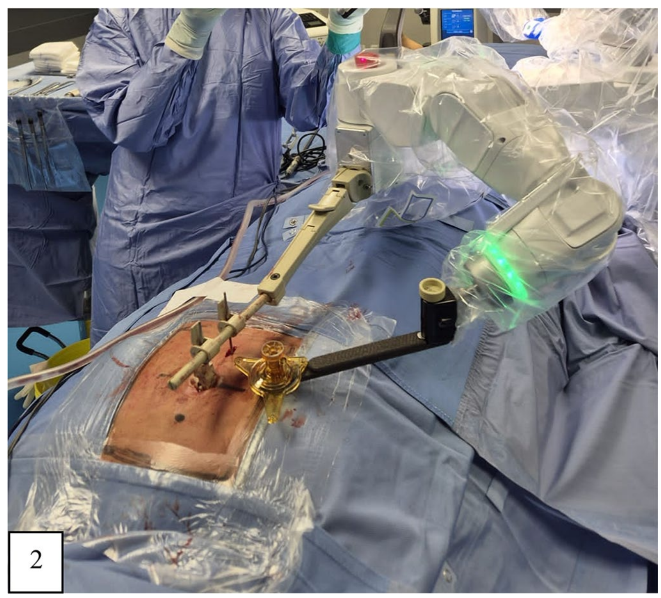


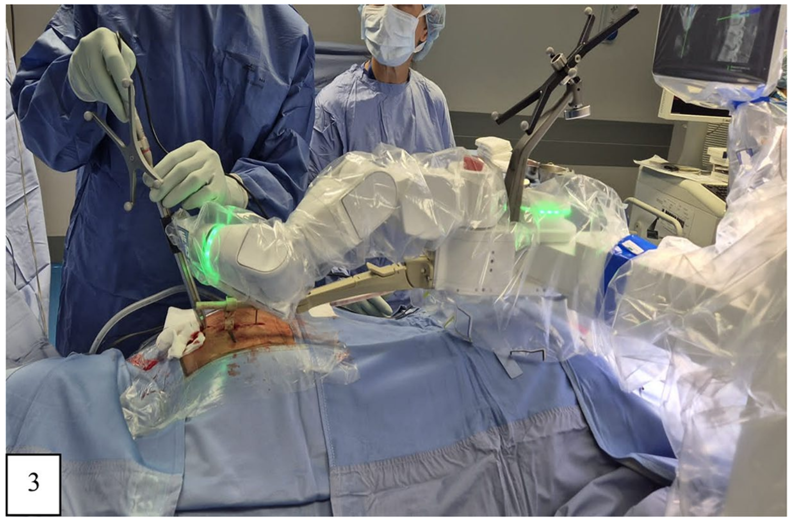
Fig. 2 Starmarker in the correct position before taking the o-arm scan

an o-arm 3D scan of the bony anatomy with the radiopaque marker. Three-dimensional images are used by the Mazor robotic guidance platform software (Mazor X robotic guidance system, model TPL0059, software version 5.1.1, Mazor Robotics Ltd., Caesarea, Israel) to merge the coordinates of the patient's anatomy with the 3D map of the robotic system. The intraoperative planning is then carried out. After choosing the target vertebra by selecting it on the robot's screen, the robotic arm is sent to the correct position. Skin and fascia are incised, then the cannula/dilator assembly is inserted into the arm guide until the dilator contacts the pedicle surface. The dilator is removed, leaving the cannula in position. Through the cannula, a navigated high-speed drill is used to prepare the pedicle for screw insertion (Fig. 3). The screw is then inserted in the pedicle through the robotic guide after removing the cannula (Fig. 4). After repeating this procedure for each screw, they are connected with the rods as it is done in traditional FAS. A final radiologic exam is taken to confirm the correct position of the fixation devices.

Results

In the RSS group, patients were aged between 22 and 83, with a mean of 60±14, 71 females and 59 males. In the FAS group, patients were aged between 27 and 89, with a

Fig. 3 Preparation for robotic pedicle screw placement with navigated high-speed drill



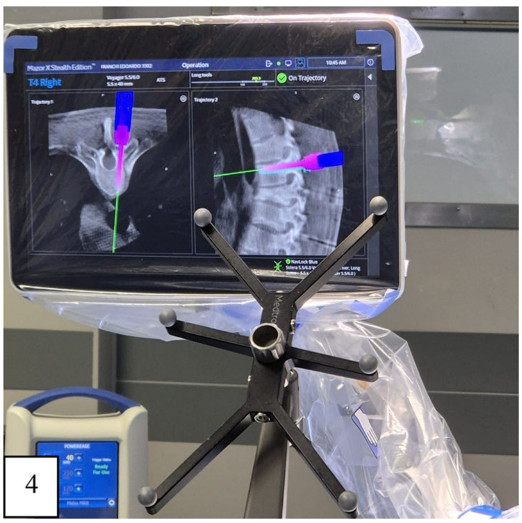


Fig. 4 Detail of the robot screen during screw placement

Table 1 Accuracy of pedicle screws in RSS and FAS groups was evaluated with Gertzbein-Robbins classification

Accuracy of screw placement	
Robotic	Fluoroscopic-assisted
98% grade A	47% grade A
2% grade B	50% grade B
	3% grade C

mean of 61±14, 69 females and 61 males. In each group, 126 patients were affected by degenerative spinal pathology, 4 by traumatic pathology. In the RSS group, 80 cases were carried out with percutaneous technique, 50 cases with open technique. In the FAS group, 13 cases were carried out with percutaneous technique, 117 cases with open technique. Mean OR entry-start surgery, total operative, and single-screw implantation times were respectively 63 minutes, 185 minutes, and 2 minutes 30 seconds in the RSS group and 46 minutes, 136 minutes, and 8 minutes 10 seconds in the FAS group. In the RSS group, 119 cases were carried out using intraoperative planning (scan ad plan) and 11 cases with pre-built planning (CT to fluoro). In the RSS group, the total number of screws placed was 757; in the FAS group, it was 652. In the RSS group, 98% of the screws were grade A, 2% grade B. In the FAS group, 47% were grade A, 50% grade B, 3% grade C (Table 1). In the RSS group, the total number of cages positioned was 109; in the FAS group, it was 39. In the RSS group, the number of revisions was 4; in the FAS group, it was 5. In the RSS group, the average length of hospital stay was 4.9 days; in the FAS group, it was 4.6 days. In the RSS group, the number of patients undergoing transfusion due to large blood losses during the operation was 11; in the FAS group, it was 12. In the RSS group and in the FAS group, the number of infections was 4 for each. From a clinical point of view, a 10% difference in means was observed to the last follow-up between the ODI of the patients operated with robotic (5%) and fluoroscopic-assisted (15%) techniques. In the cases performed with the robotic technique, 3 (2.3%) cases of junctional syndrome occurred; 17 (13.1%) in the cases performed with the fluoroscopic-assisted technique. The average radiation dose per single screw in cases performed with the CT to fluoro robotic technique (11) was 5cGycm^2. The average radiation dose per single screw in cases performed with the scan and plan robotic technique (119) was 10cGycm^2. The average radiation dose per single screw in cases performed with the percutaneous fluoroscopic-assisted technique (13) was 175cGycm^2. The average radiation dose per single screw in cases performed with the open fluoroscopic-assisted technique (117) was 40cGycm^2.

Statistical analysis

Continuous variables, including age, Oswestry Disability Index (ODI), hospitalization time, number of screws/cages implanted, OR entry-start surgery time, and duration of the operation were compared between RSS and FAS groups using independent samples t-tests. Statistically significant differences were observed in ODI ($p = 0.001$), OR entry-start surgery time ($p = 2.04 \times 10^{-17}$) and duration of the operation ($p = 4.50 \times 10^{-12}$), while no significant differences were found for age ($p = 0.579$), number of screws ($p = 0.827$), cages implanted ($p = 0.226$) and hospitalization time ($p = 0.099$). Categorical variables, such as blood transfusions, infection rate, revision surgery, and junctional pathology were compared using Chi-square tests. No significant differences were found in the need for transfusions ($p = 0.914$), infection rate ($p = 0.992$), revision surgery ($p = 0.992$), or incidence of junctional pathology ($p = 0.114$). A p-value of less than 0.05 was considered indicative of statistical significance for all comparisons (Table 2).

Role of the nursing team in robotic spine surgery

We created a group of two scrub nurses and two OR nurses dedicated to RSS. They underwent individual training with the medical engineering staff of the manufacturing company of the robot (with certification), three meetings with an expert surgeon regarding principles of spinal surgery, navigation, applications of robotic surgery, and a training of three months in the OR. We evaluated the impact that the setting of the dedicated team had on surgical interventions in terms of: OR entry-start surgery time, implant time, number of screws implanted, and duration of the intervention. A comparison was carried out between the period before the team was set up and after the training. Pre- and intraoperative times were recorded using an electronic register. By setting up the specialized nursing team, we found a reduction in the times to start surgeries. In the intraoperative phase, we recorded a higher number of screws implanted in the same amount of time. Above all, we recorded a clear reduction in the overall duration of the procedures (Table 3).

Table 2 Results of the statistical analysis

Parameter	p-value	Interpretation
Age	$p = 0.579$	Not significant
OR entry-start surgery	$p = 2.04 \times 10^{-17}$	Significant
Duration	$p = 4.50 \times 10^{-12}$	Significant
Number of screws	$p = 0.827$	Not significant
Number of cages	$p = 0.226$	Not significant
Blood trasfusion	$p = 0.914$	Not significant
Infection	$p = 0.992$	Not significant
Revision	$p = 0.992$	Not significant
Hospitalization time	$p = 0.099$	Not significant
ODI	$p = 0.001$	Significant
Junctional pathology	$p = 0.114$	Not significant

Discussion

From what emerges in this study and the literature analyzed, RSS could be successfully exploited both in traumatic and degenerative pathologies, using minimally invasive or open approaches [12–31]. Screw implantation times were certainly in favor of RSS, with an average difference of 5 minutes and 40 seconds per screw. However, despite this intraoperative advantage, the overall duration of robotic procedures was longer compared to FAS (185 vs. 136 minutes on average). This apparent paradox could be explained by several workflow-related factors. First, the OR entry-to-start time for RSS was significantly higher (63 vs. 46 minutes), reflecting the time required for robotic setup, including patient registration, reference frame positioning, imaging acquisition, and intraoperative planning on the robotic platform. Additionally, the learning curve of both the surgeons and the operating room staff played a crucial role. Once the screw implantation phase had begun, robotic guidance considerably shortened the time per screw (2’30’’ vs. 8’10’’), but this gain was not sufficient to offset the longer setup and registration time, especially in shorter constructs. Over time, as the team became more experienced and a dedicated nursing team had been established, as shown in this study, reducing average intervention duration from 253 to 190 minutes, this gap was progressively reduced. Another important aspect was the reduction of operator fatigue, who would not have to keep the X-ray protections on for hours because of the less exposure to radiation. It was important to notice that the number of infections, revisions, transfusions, and average post-operative hospital stay were similar in both groups, without any statistically significant difference. Another fundamental advantage of RSS was the accuracy of pedicle screws, which was particularly important in

Table 3 Comparison of OR entry-start surgery time, implant time, number of screws implanted and duration of the intervention before and after the introduction of the dedicated nursing team for robotic surgery

Parameters (means)	No dedicated nursing team	Dedicated nursing team
OR entry-start surgery time	67.5 min	60 min
Total implant time	30 min	30 min
Number of screws implanted	4.3	6.3
Duration of the intervention	253 min	190 min

cases of complex anatomy associated with osteoporosis, in which a greater pedicle density could be guaranteed, reducing the risk of failure of the implant. In the RSS group, in fact, 98% of the screws were grade A, 2% grade B. In the FAS group, 47% were grade A, 50% grade B, 3% grade C. In the most recent clinical follow-up, a difference of 10% was also highlighted between the means of ODI of patients who underwent RSS (5%) and FAS (15%), with a statistically significant difference. Although pain is a subjective parameter, this study shows that patients operated on by RSS had frequently less postoperative pain, which could be attributed to less trauma to the soft tissues and better accuracy in positioning the pedicle screws. Furthermore, the minimal clinically important difference (MCID) for ODI is generally accepted to be around 10%. Therefore, the observed 10% reduction in the RSS group compared to the FAS group reached clinical relevance, supporting the effectiveness of the robotic approach. A limit of this study was that in the RSS group, eighty cases were carried out with percutaneous technique and fifty with open technique, while in the FAS group, thirteen were percutaneous and one hundred seventeen were open. This disparity reflected the natural evolution of surgical practice with the introduction of robotics, but may have influenced differences in postoperative pain outcomes. Regarding the junctional pathology, even if there was no statistically significant difference between the two groups, what we could highlight was a trend in favor of RSS such that the seventeen patients operated on using the fluoroscopic-assisted technique presented junctional pathology, while only three of those operated on using the robotic technique. However, one-year follow-up was a relatively short period, which might not be adequate to fully capture the incidence of adjacent segment degeneration, a condition that often necessitates longer-term observation for accurate assessment. Anyway, this preliminary result could be explained by the fact that there was less damage to the adjacent articular processes. The main limitation of this study was the size of the sample examined, so larger case studies will be necessary to analyze differences and indications of FAS and RSS [32]. Robotics has also the potential to enhance other aspects of surgical procedures (such as discectomy, laminectomy, and endoscopy) beyond pedicle screw placement, so we will certainly explore these future prospects [33]. Another important aspect is that studies of complications and cost-effectiveness are still very rare [34].

Conclusions

In our experience, RSS has important advantages compared to FAS in terms of accuracy of pedicle screw positioning. It reduces implantation times and postoperative pain without additional complications. The preparatory stages can be time-consuming and must be carried out with the greatest possible care. The learning curve not only of the surgeon, but of all the operating room staff, represents a crucial point in the speed of execution of the procedure.

Acknowledgments None of the authors has any potential conflict of interest.

Author contributions All authors contributed equally to the conception, drafting, and revision of this manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

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

Declarations

Conflict of interest The authors declare no competing interests.

References

1. Cornwall GB, Davis A, Walsh WR, Mobbs RJ, Vaccaro A (2020) Innovation and new technologies in spine surgery, circa 2020: a fifty-year review. Front Surg 7:575318. https://doi.org/10.3389/fsurg.2020.575318
2. Boddapati V, Lombardi JM, Urakawa H, Lehman RA (2021) Intraoperative image guidance for the surgical treatment of adult spinal deformity. Ann Transl Med 9(1):91–91. https://doi.org/10.21037/atm-20-2765
3. Alluri RK, Avrumova F, Sivaganesan A, Vaishnav AS, Lebl DR, Qureshi SA (2021) Overview of robotic technology in spine surgery. HSS J 17(3):308–316. https://doi.org/10.1177/15563316211026647
4. Mamdouhi T, Wang V, Echevarria AC, Katz A, Morris M, Zavurov G, Verma R (2024) A comprehensive review of the historical description of spine surgery and its evolution. Cureus 16(2):e54461. https://doi.org/10.7759/cureus.54461
5. Wilson JP Jr., Fontenot L, Stewart C, Kumbhare D, Guthikonda B, Hoang S (2024) Image-guided navigation in spine surgery: from historical developments to future perspectives. J Clin Med. https://doi.org/10.3390/jcm13072036
6. Al-Naseem AO, Al-Muhannadi A, Ramadhan M, Alfadhli A, Marwan Y, Shafafy R, Abd-El-Barr MM (2024) Robot-assisted pedicle screw insertion versus navigation-based and freehand techniques for posterior spinal fusion in scoliosis: a systematic review and meta-analysis. Spine Deform 12(5):1203–1215. https://doi.org/10.1007/s43390-024-00879-y
7. Farber SH, Pacult MA, Godzik J, Walker CT, Turner JD, Porter RW, Uribe JS (2021) Robotics in spine surgery: a technical overview and review of key concepts. Front Surg 8:578674. https://doi.org/10.3389/fsurg.2021.578674
8. Xie LZ, Wang QL, Zhang Q, He D, Tian W (2023) Accuracies of various types of spinal robot in robot-assisted pedicle screw insertion: a Bayesian network meta-analysis. J Orthop Surg Res 18(1):243. https://doi.org/10.1186/s13018-023-03714-8
9. Li C, Li W, Gao S, Cao C, Li C, He L, Ma X, Li M (2021) Comparison of accuracy and safety between robot-assisted and conventional fluoroscope assisted placement of pedicle screws in thoracolumbar spine: a meta-analysis. Medicine (Baltimore) 100(38):e27282. https://doi.org/10.1097/MD.0000000000027282

10. Li X, Chen J, Wang B, Liu X, Jiang S, Li Z, Li W, Li Z, Wei F (2024) Evaluating the status and promising potential of robotic spinal surgery systems. Orthop Surg 16(11):2620–2632. https://doi.org/10.1111/os.14244
11. Peng YN, Tsai LC, Hsu HC, Kao CH (2020) Accuracy of robot-assisted versus conventional freehand pedicle screw placement in spine surgery: a systematic review and meta-analysis of randomized controlled trials. Ann Transl Med 8(13):824. https://doi.org/10.21037/atm-20-1106
12. Antonacci CL, Zeng F, Block A, Davey A, Makanji H (2024) Robotic-assisted spine surgery-a narrative review. J Spine Surg 10(2):305–312. https://doi.org/10.21037/jss-23-40
13. Buza JA 3rd, Good CR, Lehman RA Jr., Pollina J, Chua RV, Buchholz AL, Gum JL (2021) Robotic-assisted cortical bone trajectory (CBT) screws using the Mazor X Stealth Edition (MXSE) system: workflow and technical tips for safe and efficient use. J Robot Surg 15(1):13–23. https://doi.org/10.1007/s11701-020-01147-7
14. Caelers I, Berendsen RCM, Droeghaag R, Pecasse NJJ, Rijkers K, Van Hemert WLW, De Bie RA, Van Santbrink H (2023) Comparing radiation dose of image-guided techniques in lumbar fusion surgery with pedicle screw insertion; a systematic review. N Am Spine Soc J 13:100199. https://doi.org/10.1016/j.xnsj.2023.100199
15. Campbell DH, McDonald D, Araghi K, Araghi T, Chutkan N, Araghi A (2021) The clinical impact of image guidance and robotics in spinal surgery: a review of safety, accuracy, efficiency, and complication reduction. Int J Spine Surg 15(s2):S10–S20. https://doi.org/10.14444/8136
16. Cui GY, Han XG, Wei Y, Liu YJ, He D, Sun YQ, Liu B, Tian W (2021) Robot-assisted minimally invasive transforaminal lumbar interbody fusion in the treatment of lumbar spondylolisthesis. Orthop Surg 13(7):1960–1968. https://doi.org/10.1111/os.13044
17. Epstein NE (2021) Perspective on robotic spine surgery: who's doing the thinking? Surg Neurol Int 12:520. https://doi.org/10.25259/SNI_931_2021
18. Guan J, Feng N, Yu X, Yang K (2024) Comparison of robot-assisted versus fluoroscopy-guided transforaminal lumbar interbody fusion (TLIF) for lumbar degenerative diseases: a systematic review and meta-analysis of randomized controlled trails and cohort studies. Syst Rev 13(1):170. https://doi.org/10.1186/s13643-024-02600-6
19. Heydar AM, Tanaka M, Prabhu SP, Komatsubara T, Arataki S, Yashiro S, Kanamaru A, Nanba K, Xiang H, Hieu HK (2024) The impact of navigation in lumbar spine surgery: a study of historical aspects, current techniques and future directions. J Clin Med. https://doi.org/10.3390/jcm13164663
20. Huang M, Tetreault TA, Vaishnav A, York PJ, Staub BN (2021) The current state of navigation in robotic spine surgery. Ann Transl Med 9(1):86. https://doi.org/10.21037/atm-2020-ioi-07
21. Jung B, Han J, Shahsavarani S, Abbas AM, Echevarria AC, Carrier RE, Ngan A, Katz AD, Essig D, Verma R (2024) Robotic-assisted versus fluoroscopic-guided surgery on the accuracy of spine pedicle screw placement: a systematic review and meta-analysis. Cureus 16(2):e54969. https://doi.org/10.7759/cureus.54969
22. Lajczak P, Zerdzinski K, Jozwik K, Laskowski M, Dymek M (2024) Enhancing precision and safety in spinal surgery: a comprehensive review of robotic assistance technologies. World Neurosurg 191:109–116. https://doi.org/10.1016/j.wneu.2024.08.051
23. 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 Musculoskelet Disord 23(1):328. https://doi.org/10.1186/s12891-022-05206-y
24. Lu Z, Tischer T, Lutter C, Schnake KJ (2024) Robotic-assisted surgery for adult spinal deformity. A systematic review. Brain and Spine 4:102904. https://doi.org/10.1016/j.bas.2024.102904
25. Mensah EO, Chalif JI, Baker JG, Chalif E, Biundo J, Groff MW (2024) Challenges in contemporary spine surgery: a comprehensive review of surgical, technological, and patient-specific issues. J Clin Med. https://doi.org/10.3390/jcm13185460
26. Perez de la Torre RA, Ramanathan S, Williams AL, Perez-Cruet MJ (2022) Minimally-invasive assisted robotic spine surgery (MARSS). Front Surg 9:884247. https://doi.org/10.3389/fsurg.2022.884247
27. Perna A, Velluto C, Smakaj A, Tamburrelli F, Borruto MI, Santagada DA, Gorgoglione FL, Liuzza F, Proietti L (2023) Positioning accuracy and facet joints violation after percutaneous pedicle screws placement with robot-assisted versus fluoroscopy-guided technique: systematic review and meta-analysis. J Neurosci Rural Pract 14(3):406–412. https://doi.org/10.25259/JNRP_147_2023
28. Rawicki N, Dowdell JE, Sandhu HS (2021) Current state of navigation in spine surgery. Ann Transl Med 9(1):85. https://doi.org/10.21037/atm-20-1335
29. Tarawneh AM, Salem KM (2021) A systematic review and meta-analysis of randomized controlled trials comparing the accuracy and clinical outcome of pedicle screw placement using robot-assisted technology and conventional freehand technique. Glob Spine J 11(4):575–586. https://doi.org/10.1177/2192568220927713
30. Yongqi L, Dehua Z, Hongzi W, Ke Z, Rui Y, Zhou F, Shaobo W, Yi L (2020) Minimally invasive versus conventional fixation of tracer in robot-assisted pedicle screw insertion surgery: a randomized control trial. BMC Musculoskelet Disord 21(1):208. https://doi.org/10.1186/s12891-020-03239-9
31. Li Y, Wang Y, Ma X, Ma J, Dong B, Yang P, Sun Y, Zhou L, Shen J (2023) Comparison of short-term clinical outcomes between robot-assisted and freehand pedicle screw placement in spine surgery: a meta-analysis and systematic review. J Orthop Surg Res 18(1):359. https://doi.org/10.1186/s13018-023-03774-w
32. Sielatycki JA, Mitchell K, Leung E, Lehman RA (2022) State of the art review of new technologies in spine deformity surgery-robotics and navigation. Spine Deform 10(1):5–17. https://doi.org/10.1007/s43390-021-00403-6
33. Malham GM, Wells-Quinn TA, Nowitzke AM, Mobbs RJ, Sekhon LH (2024) Challenges in contemporary spinal robotics: encouraging spine surgeons to drive transformative changes in the development of future robotic platforms. J Spine Surg 10(3):540–547. https://doi.org/10.21037/jss-24-4
34. Sun WX, Huang WQ, Li HY, Wang HS, Guo SL, Dong J, Chen BL, Lin YP (2023) Clinical efficacy of robotic spine surgery: an updated systematic review of 20 randomized controlled trials. EFORT Open Rev 8(11):841–853. https://doi.org/10.1530/EOR-23-0125