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Review Article

Current Concepts of Spine Robotic Assistance versus Freehand Techniques in Spine Surgery: A Systematic Review and Meta-Analysis

Daniel Encarnacion-Santos[1,*], Gennady Chmutin[2], Egor Chmutin[3], Ismail Bozkurt[4], Bipin Chaurasia[5]

[1] Resident, Department of Neurosurgery, Peoples' Friendship University of Russia, Moscow, Russia
[2] Professor, Department of Neurosurgery of People of Friendship University, Moscow, Russia
[3] Associate Professor, Department of Neurosurgery of People of Friendship University, Moscow, Russia
[4] Assistant Professor, Department of Neurosurgery, Medical Park Ankara Hospital, Ankara, Turkey
[5] Department of Neurosurgery, Neurosurgery Clinic, Birgunj, Nepal

[*]Corresponding author: Daniel Encarnacion Santos; Department of Neurosurgery, Peoples' Friendship University of Russia, Moscow, Russia. Tel: +79-253847196
Email: danielencarnacion2280@gmail.com

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Abstract

Background: Robotic assistance in spinal surgery has completely changed the face of the practice over recent decades. The concept of pedicle screw fixation, introduced in the early 1950s, has grown to be one of the cornerstones of treatment for various spinal pathologies. The purpose of this study is to evaluate surgical outcomes and different treatment modalities in spinal pathologies by comparing robotic-assisted techniques with conventional freehand techniques.
Methods: A systematic review and meta-analysis were performed based on the PRISMA guidelines. A literature search was conducted using major databases such as ScienceDirect and PubMed/MEDLINE. Statistical analyses were performed using IBM SPSS software, R software, and Microsoft Excel. Peer-reviewed studies published in the English language up to January 2025 were included.
Results: Results were compiled from a total of 2,592 patients who underwent robotic neuronavigation-guided spinal surgery, reflecting the precision and efficacy of state-of-the-art robotic technologies in spinal surgery. Of these, 2,219 patients were treated with robotic-assisted pedicle screw placement, while 2,294 patients were treated with conventional freehand or fluoroscopy-guided techniques.
Conclusion: Our findings have shown that robotically assisted spine surgery is indeed more accurate, with reported rates of up to 90% precision in pedicle screw placement compared to freehand techniques.

Keywords: Spinal Cord Injuries; Surgical Navigation Systems; Computer-Assisted Surgery; Robotic Surgical Procedures; Rehabilitation

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Background

Robotic-assisted surgery in spine procedures has considerably altered modern surgical practice. Pedicle screw fixation, first developed in the early 1950s, is a standard method for stabilizing a wide variety of spinal disorders. Over the last decades, navigation techniques have undergone major development owing to an increase in accuracy with image-guided and robotic-assisted systems (1).

The early origins of minimally invasive spine surgery (MISS) involved some unsuccessful efforts at intraluminal approaches to lumbar hernias in the 1980s. After the overdue introduction of the surgical microscope for herniated disc removal by Yasargil and Caspar in 1977, spinal microsurgery began to evolve. Furthermore, in 1983, arthroscopic treatment for lumbar disc disease emerged, followed by Kambin's 1996 description of the posterolateral access zone, now known as the Kambin triangle-a critical anatomical landmark in MISS (2). Additionally, the development of percutaneous transpedicular vertebroplasty and kyphoplasty between 1984 and 2000 revolutionized the treatment of osteoporotic fractures (3).

Despite these innovations, MISS was not initially widely accepted due to concerns about radiation exposure from fluoroscopy-guided techniques. This concern thus led to the development of computer-assisted, or PC-assisted, surgical navigation systems in the mid-1980s, with CT-based navigation playing a pivotal role in advancing robotic-assisted spinal surgery (4). Currently, robotic systems in spinal surgery are developed with the aim to replace traditional fluoroscopic guidance with more accurate, real-time robotic-assisted pedicle screw placement. Nevertheless, their integration into clinical practice has to be considered in light of various key factors, which include surgical accuracy, cost-effectiveness, accessibility, and inventory management. The significant financial investment required for robotic platforms remains a critical barrier to their widespread adoption and clinical efficacy (5).

This study aims to explore postoperative outcomes of robotic-assisted spine surgery using Tirobot, Mazor, and ROSA robotic systems and compare them to conventional freehand, fluoroscopic, and exoscopic surgical techniques. It seeks to determine whether robotic assistance enhances surgical accuracy while reducing complications and pain during the postoperative period.

Methods

A systematic review and meta-analysis were conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to compare surgical outcomes of robotic-assisted techniques with freehand techniques for spinal pathologies.

Search Strategy and Data Sources

A complete search of the literature was performed across multiple databases including ScienceDirect and PubMed/MEDLINE for relevant studies. The search strategy was developed to include "spine robotics" combined with specific surgical techniques, rehabilitation methods, and related spinal pathologies. Studies published in English and available before January 2025 were included in this analysis. The search strategy incorporated MeSH terms (Medical Subject Headings) related to spine robotics:

- "Robotics spine/history"(Mesh)
- "Robotics spine/complications"(Mesh)
- "Robotics spine/diagnosis"(Mesh)
- "Robotics spine/diagnostic imaging"(Mesh)
- "Robotics spine/drug therapy"(Mesh)
- "Robotics spine/epidemiology"(Mesh)
- "Robotics spine/etiology"(Mesh)
- "Robotics spine/mortality"(Mesh)
- "Robotics spine/pathology"(Mesh)
- "Robotics spine/physiopathology"(Mesh)
- "Robotics spine/prevention and control"(Mesh)
- "Robotics spine/psychology"(Mesh)
- "Robotics spine"(Mesh)
- "Robotics spine/rehabilitation"(Mesh)
- "Robotics spine/surgery (Mesh)
- "Robotics spine/ free hand "(Mesh)
- "Robotics/classification"(Mesh)
- "Robotics/ethics"(Mesh)
- "Robotics/history"(Mesh)
- "Robotics/instrumentation"(Mesh)
- "Robotics/methods"(Mesh)
- "Robotics/statistics and numerical data"(Mesh)

Additional keywords: Additional keywords included "robotic spine, spinal pathologies," "fractures," "spondylolisthesis," "scoliosis," "osteoporosis," "spine," "trauma and imaging," "surgical approaches," and "restoration or rehabilitation."

Eligibility Criteria and Study Framework

The study enrolled patients aged 18-85, undergoing spinal surgery using Tirobot, TINAVI, ExcelsiusGPS system, Mazor, and other freehand robotic systems based on the Population, Intervention, Comparison, and Outcome (PICO) framework. The main spinal conditions considered in the research were:

-Degenerative pathologies, such as spondylolisthesis and scoliosis

-Traumatic fractures such as vertebral and thoracolumbar fractures

Relevant studies were systematically reviewed in order to compare the accuracy, safety, and clinical outcomes of robotic-assisted and freehand techniques in spinal surgery (Figure 1).

Inclusion Criteria

- Age Range: Patients aged 18-85 years
- Spinal Pathologies: Investigations concerning spinal stabilization performed with robotic systems, including, Tirobot, TINAVI, Mazor, and other novel robotic-assisted platforms
- Surgical Approaches: Robotic-assisted approaches compared against traditional freehand, fluoroscopic, or exoscopic approaches in treating scoliosis, spondylolisthesis, and spinal fractures, thoracolumbar disorders, atlantoaxial pathologies, or cervical disorders
- Imaging and navigation: The role of neuronavigation and MRI-based imaging in diagnosing and planning surgery for the pathologies of the spine, especially regarding accuracy in pedicle screw placement
- Clinical outcome: Neurological recovery following robotic-assisted and freehand spinal fixation, including stabilization with fluoroscopic guidance for correction of deformities

Exclusion Criteria

- Pediatric: Below 18 years of age
- ***Non-surgical cases:*** Patients presenting with symptoms suggestive of spinal disorders but excluded from surgery based on imaging findings that did not meet the inclusion criteria

Robotic-Assisted Kyphoplasty for Osteoporotic Vertebral Compression Fractures

Kyphoplasty for osteoporotic vertebral compression fractures was performed with robotic assistance, utilizing a prone positioning technique with unilateral spinal puncture under anesthesia. The TiRobot® system (TINAVI Medical Technologies Co., Ltd., Beijing, China), widely used in Beijing, China, was employed for this procedure due to its optical tracking system, controlled robotic arm, and 6 degrees of freedom, allowing for precise Kirschner wire implantation.

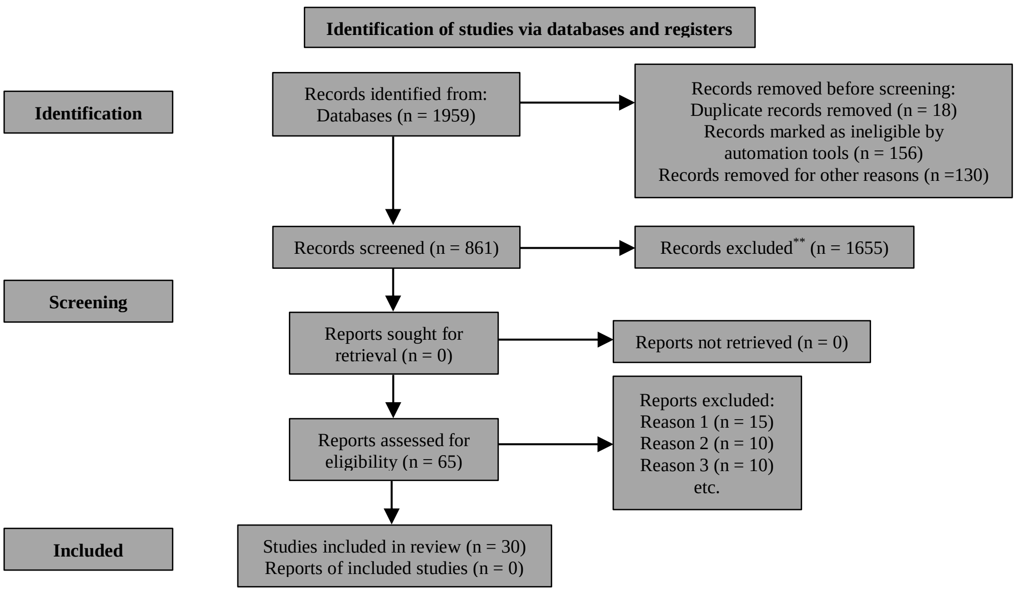


Figure 1. PRISMA flowchart illustrating the study selection process for the systematic review on robotic spine neuronavigation and pedicle screw placement

For optimal robotic-assisted kyphoplasty, the fixed tracker was positioned on the patient's surface using sterile tape, and the robot was covered with a sterile drape. Fluoroscopic guidance was used for accurate robot positioning before initiating the three-dimensional scan. The C-arm (Arcadis Orbic 3D; Siemens, Munich, Germany) performed a 190-degree scan, allowing for trajectory planning of the unilateral puncture.

The robotic arm assisted in precise vertebral body puncture with the Kirschner wire, followed by verification using fluoroscopy in both anteroposterior and lateral views. A 0.5 cm skin incision was made approximately 2 cm lateral to the pedicle projection, allowing for a unilateral approach at an abduction angle of 30 degrees.

The Jamshidi trocar was then advanced to the pedicle surface, and once properly aligned, the trocar was inserted toward the vertebral body. A deflated balloon was then introduced into the vertebral body, which was inflated under manometric control to restore the collapsed vertebral height while creating an internal cavity for cement augmentation (6-24).

TiRobot-Assisted Surgical Equipment and Procedure

The TiRobot-assisted surgical procedure follows a protocol similar to fluoroscopy-assisted spinal procedures, with the patient positioned under general anesthesia. The C-arm arch is used to localize the affected or fractured vertebral segment, ensuring precise targeting.

A percutaneous tracker is placed on the upper spinous process of the instrumented segment, serving as a reference for the robotic system. The robotic arm then positions a caliper on the surface of the skin over the affected vertebra. A three-dimensional (3D) scan is performed using the C-arm, and the generated images are transferred to the robotic system.

Once the surgical plan is finalized, robotic commands are issued, guiding the robotic arm to the designated position. A 2 cm skin incision is made using the robotic guide handle, and the vertebrae are drilled with a guide wire.

The placement and reduction of pedicle screws are then performed, with an accuracy compared to conventional fluoroscopy-assisted techniques (14).

Data Collection

Data was curated from studies of end-to-end minimally invasive spinal intervention using robotic-assisted neuronavigation, focusing on:

- Spinal pathologies such as spondylolisthesis, trauma and fractures, prolapsed intervertebral discs, scoliosis, and osteoporosis
- Technique of surgical stabilization, specifically, pedicle screw implantation for spinal stabilization
- Factors contributing to spinal myelopathies and radiculopathies, with particular emphasis on degenerative and osteochondrosis
- Comparative assessment of surgical and conservative treatments, such as early decompression strategies and spinal pain management
- Approach to rehabilitation of the spinal cord using neuronavigation and robotic-assisted recovery protocols.

Precision in Pedicle Screw Placement

Postoperatively, cervical spine reconstructive surgery outcomes were assessed using computed tomography (CT) scans performed 2 days after surgery to evaluate screw placement accuracy based on the Gertzbein and Robbins classification. Screws were categorized as follows:

- ***Grade 0:*** Fully contained within the pedicle
- ***Grade I:*** Perforation of the cortex < 2 mm
- ***Grade II:*** Perforation between ≥2 mm and < 4 mm
- ***Grade III:*** Perforation ≥4 mm.

Screws classified as grade 0 and grade I were deemed clinically acceptable, whereas grade II and III screws were considered malpositioned, with a higher likelihood of neurovascular complications. In cases of suspected misplacement, CT angiography or MRI angiography was used to assess potential vertebral injuries (10, 11, 23).

Degree of Screw Violation

The degree of screw violation in the external jugular vein of the proximal adjacent segment was assessed using the modified Seo classification. According to this classification:

- ***Grade 0:*** No violation is observed.
- ***Grade 1:*** The screw head, axis, or the entire screw does not extend beyond or penetrate the facet joint but may be in close proximity (≤1 mm), without violating the articular facet.
- **Grade 2:** The screw head, axis, and body are clearly within the facet joint.

This classification also considers adjacent cranial segment involvement in patients with degenerative spinal diseases, particularly in cases where facet joint destruction is observed. Additionally, it is applied to all fixation segments in trauma patients, including those who do not require decompression procedures. For facet joint violations, the consensus classification is referenced to ensure standardization (3-25).

Data Extraction and Analysis

A standardized data extraction process was utilized, enlisting the support of PubMed/ MEDLINE and Cochrane databases to make a comprehensive and strict selection of research manuscripts relevant to the topic at hand. The search was specifically addressed to robotic spinal interventions, including neuronavigation and freehand fluoroscopy-based techniques.

Data extracted included, but was not limited to:

- Demographics of the studied populations
- Intervention and control parameters in comparative studies
- Authors, year of publication, and study design
- Spinal fixation/stabilization via robotic versus conventional techniques

Risk of Bias Assessment

All the included studies were appraised for quality on systematic review and meta-analysis to ensure methodological rigor. The risk of bias for each study was determined by standard tools, as per PRISMA.

- Studies with low risk of bias in the design of intervention and blinding of results were selected to ensure validity in the assessment of outcomes.
- Non-randomized studies had a relatively higher risk of bias, especially in participant selection.
- The bias evaluation tools were used accordingly to ensure that the data interpretation was robust and presented good methodological consistency.

Statistical Analysis

Data analysis was performed using IBM SPSS software (version 26.0, 2020; IBM Corp., Armonk, NY, USA), R software (5.4; R Foundation, Vienna, Austria), and Microsoft Excel (Microsoft Corp., Redmond, WA, USA) to compare the efficacy of robotic-assisted techniques and conventional minimally invasive surgical techniques in spinal surgery.

- Data presentation: Results are presented as mean values ± standard deviation (SD).

Comparison analysis: Statistical comparison of robotic-assisted neuronavigation for spinal fixation, fusion, and stabilization with freehand techniques and fluoroscopy-guided interventions was performed.

- Statistical significance: For statistical significance, a P-value less than 0.05 was considered significant.
- Effect measures: Calculations for mean differences and odds ratios, with respect to observed outcomes, were computed.
- Model selection: A random-effects model was used in estimating the outcome measures from individual studies to make the meta-analysis calculations robust.

Results

This systematic review and meta-analysis integrated the analysis of 2,592 patients that received robotic neuronavigation-guided spinal surgery to evaluate the accuracy and effectiveness of the robotic-assisted techniques versus standard methods. Of these patients, 2,219 underwent robotic-assisted surgery, whereas 2,294 underwent freehand or fluoroscopic surgery.

A total of 2,599 pedicle screws were placed with robotic assistance, whereas 1,711 pedicle screws were inserted using the freehand technique, as detailed in table 1 and figures 2-6.

Further stratification of the patient cohort revealed that among 1,478 patients, 1,512 (58.3%) underwent robotic-assisted procedures, whereas 1,617 (62.3%) underwent freehand techniques. Pedicle screw placement in this subgroup comprised 2,599 screws placed via robotic assistance and 1,711 screws inserted using freehand methods. Another subset included 1,114 patients, of whom 707 (27.2%) underwent robotic-assisted surgery, while 677 (26.1%) underwent freehand procedures (Table 2).

Study-Specific Findings

In Beijing Jishuitan Hospital, China, during the year 2022, a retrospective study was performed on a trial group comprising 80 subjects undergoing robot-assisted pedicle screw placement and aimed to compare the accuracy of robotic-assisted and freehand thoracolumbar pedicle screw placement. Out of the total 80 subjects, 40 were assigned to robotic-assisted surgery while the other 40 underwent the freehand technique.

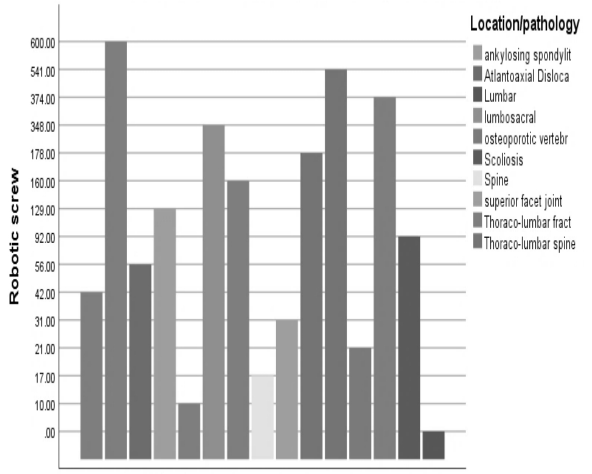


Figure 2. Patients undergoing comparative spinal surgery using freehand techniques versus robot-assisted, fluoroscope-guided, and neuronavigation-assisted approaches

Robot-assisted techniques yielded a total number of screw placements equaling 178, while freehand methods accounted for 172 screw placements. The robotic-assisted group had significantly greater accuracy: group A: 91% grade A placement, 75.6% freehand (P < 0.001). Likewise, in group B, robotic-assisted placement performed more accurately at 99.4% compared with the freehand methods at 90.1% (P < 0.001), reflecting the operational precision of second-generation robotic systems (6). A recent retrospective cohort study conducted in 2024 examined 95 patients who underwent robotic spine surgery to evaluate the learning curve of the Mazor robotic system (Medtronic, Dublin, Ireland) and track its progress alongside the ExcelsiusGPS® system (Globus Medical, PA, USA). The study observed a notable decrease in surgical time following the first 14 cases, with significant improvements in screw placement efficiency after 13 cases.

Table 1. Studies comparing patients who underwent surgery using modern robotic-assisted systems with those who underwent freehand pedicle screw placement

Author's	Study	Year	No. of patients	Freehand	Robot-assisted	Location/pathology	Robotic screw	Free hand screw	P-value	Robotic system
Yan et al. (6)	Retrospective	2022	80	40	40	Thoraco-lumbar spine	178	172	< 0.001	Tirobot system
Shi et al. (7)	Retrospective Cohort Study	2024	95	14	13	Thoraco-lumbar spine	541	N/A	0.1	ExcelsiusGPS system
Li C. et al. (8)	Retrospective	2024	144	48	44	Scoliosis	92	52	< 0.005	TiRobotTINAVI
Li Y. et al. (9)	Retrospective	2024	40	24	16	Ankylosing spondylitis	129	182	< 049	Tirobot
Zhan et al. (10)	Retrospective	2022	25	14	11	Atlantoaxial Dislocation	56	44	0.04	TINAVI
Cao et al. (11)	RCT	2021	46	15	15	Thoraco-lumbar fractures	10	11	N/A	Tirobot
Yuan et al. (12)	Retrospective study	2020	96	22	37	Osteoporotic vertebral compression fracture	21	16	> 0.05	Tirobot
Le et al. (13)	Retrospective study	2019	69	46	23	Superior facet joint violation	31	17	0.04	Horizon Solera Spinal System
Lin et al. (14)	Retrospective study	2022	126	61	65	Thoraco-lumbar fractures	374	355	< 0.05	TiRobot-assisted and fluoroscopy-assisted
Tian et al. (15)	Retrospective study	2020	58	30	28	Thoraco-lumbar fractures	160	170	< 0.05	Mazor Robotics
Peng et al. (16)	Systematic Review	2020	540	1256	1220	Lumbar	N/A	N/A	< 0.37	Mazor Robotics/ Tirobot
Yu et al. (17)	Retrospective study	2022	24	N/A	N/A	Thoraco-lumbar fractures	600	600	< 0.001	TINAVI
Villeneuve et al. (18)	Case series	2022	14	N/A	N/A	Thoraco-lumbar fractures sacral	42	84	N/A	(ExcelsiusGPS®, Globus, Audubon)
Vardiman et al. (19)	Retrospective study	2019	56	N/A	N/A	lumbosacral	348	8	N/A	ExcelsiusGPS®;Globus Medical ect.
Lee et al. (20)	Prospective single-cohort analysis	2023	65	47	N/A	Spine	17	N/A	025	Mazor Robotics

Table 2. Comparative studies of patients undergoing robotic-assisted spine surgery versus those treated with freehand screw placement, focusing on the level of intervention, underlying pathology, and surgical approach

Author's	Study	Year	Patients	Robot-assisted group	Freehand technique group	Level	Spine pathologies	Robotic
Zongze et al. (21)	Retrospective	2024	20	39	40	L4-L5	Lumbar	Orthbot
Ringel et al. (22)	RCT	2012	30	30	30	L2–S1	Lumbosacral	SpineAssist (Mazor)
Kim et al. (23)	RCT	2015	20	20	20	L2–S1	Lumbar Stenosis	Renaissance (Mazor)
Tian et al. (24)	RCT	2017	40	23	17	T1—S1	Lumbar fracture, L. spondylolisthesis	TiRobot
Schizas et al. (25)	Comparative study RCT	2012	34	64	64	T1-L5-S1	Straight or scoliotic spines	SpineAssist
Schatlo et al. (26)	Retrospective Cohort Study	2014	95	55	40	L4-L5	Lumbar spine degenerative disease	SpineAssist
Hwang et al. (27)	RCT	2024	162	54	54	L2-L5-S1	Lumbar degenerative disease	SpineAssist
Lonjon et al. (28)	Prospective case	2016	20	10	10	L1-S1	Degenerative lumbar spine disease	ROSA
Solomiichuk et al. (29)	Retrospective matched-cohort study	2017	70	35	35	T1-T6-L5-S1	Spinal metastasis	SpineAssist
Feng et al. (30)	RCT	2019	80	40	40	L1-L5	Osteoporosis	TiRobot
Fayed et al. (31)	Prospective vs retrospective	2020	20	20	28	L2-S1	Stabilizing the spine after interbody fusion	ExcelsiusGPS
Katsevman et al. (32)	Retrospective cohort	2021	37	17	20	T2-L5	Spinal fractures	Mazor X
Cui et al. (33)	Retrospective cohort	2021	48	23	25	L4-L5-S1	Lumbar spondylolisthesis	Tianji Robot
Gao et al. (34)	Retrospective cohort	2018	306	158	148	N/A	Facet joint violation	Renaissance
Su et al. (35)	RCT	2022	58	28	30	C2-C6	Posterior cervical surgery for degenerative or trauma	TiRobo TINAVI
Zhang et al. (36)	Retrospective cohort	2022	74	30	14	T11-L2	Thoracolumbar fractures	TINAVI Robot
Wang et al. (37)	RCT	2022	N/A	61	62	N/A	Lumbar spinal stenosis with instability and spondylolisthesis	TiRobot

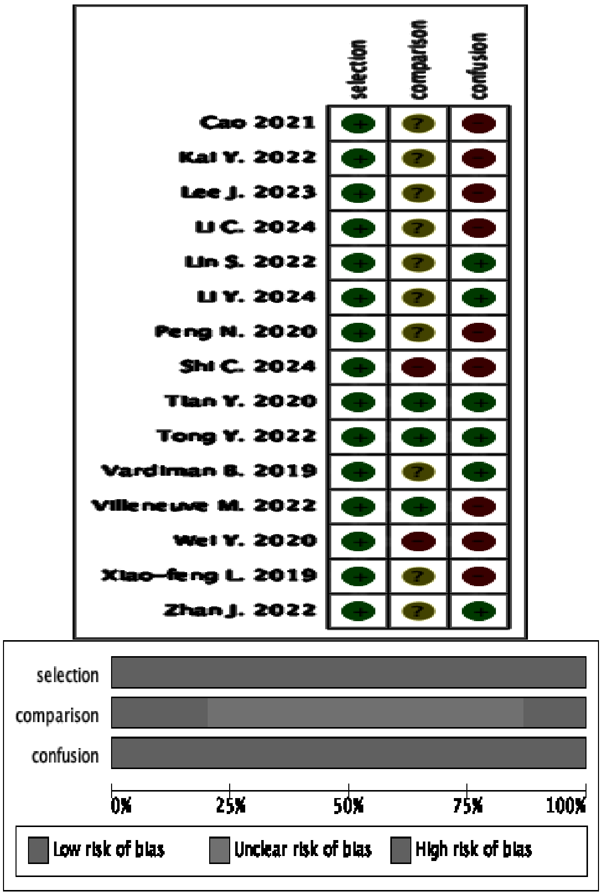


Figure 3. A) Risk of Bias Summary: Review authors' judgments for each risk of bias domain in each included study; B) Risk of Bias Graph: Proportion of studies with each judgment (low, unclear, or high risk) presented as percentages across all included studies

Over the study period from 2021 to 2022, a total of 541 pedicle screws were placed, with an analysis covering operative duration, screw placement time, and fluoroscopic guidance usage. Additionally, a comparison of 2 descriptive sample groups assessed surgical complications, highlighting variations in robotic-assisted interventions and freehand techniques (7).

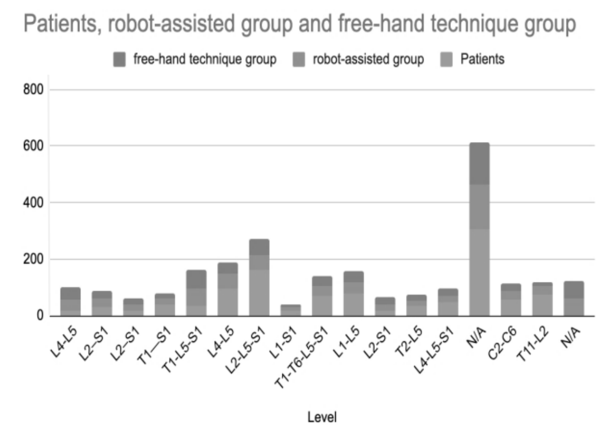


Figure 5. Patients undergoing freehand versus robot-assisted, fluoroscope-guided, or exoscope-guided neuronavigation surgery, compared by pathology type, anatomical location, and level of intervention

In 2024, a retrospective study was performed in which robotic navigation-assisted pedicle screw placement using C-arm and 3D imaging was compared with the freehand technique in a group of scoliosis patients.

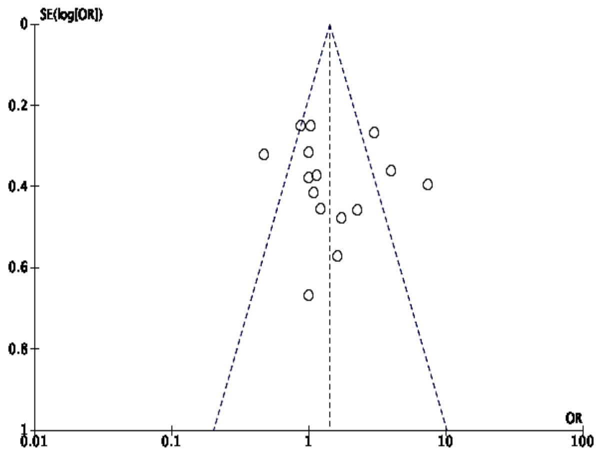
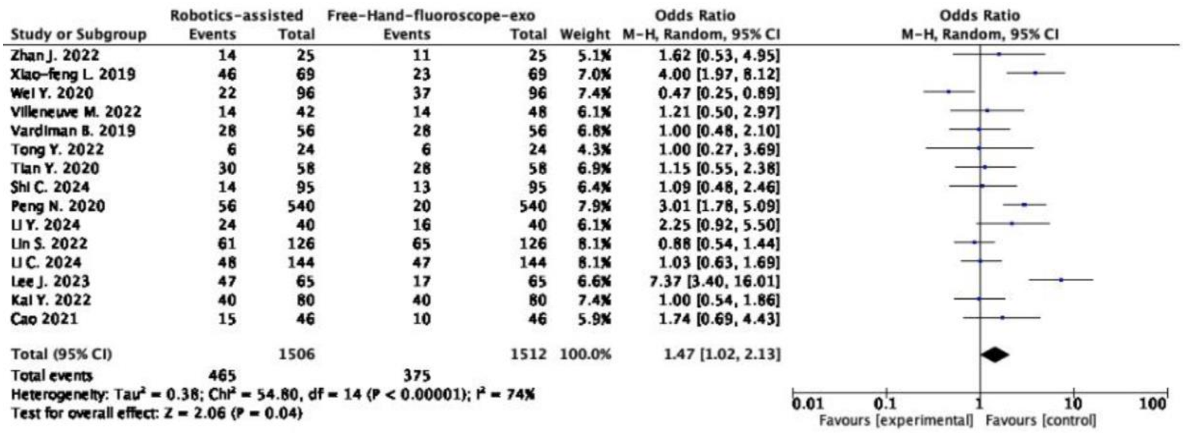
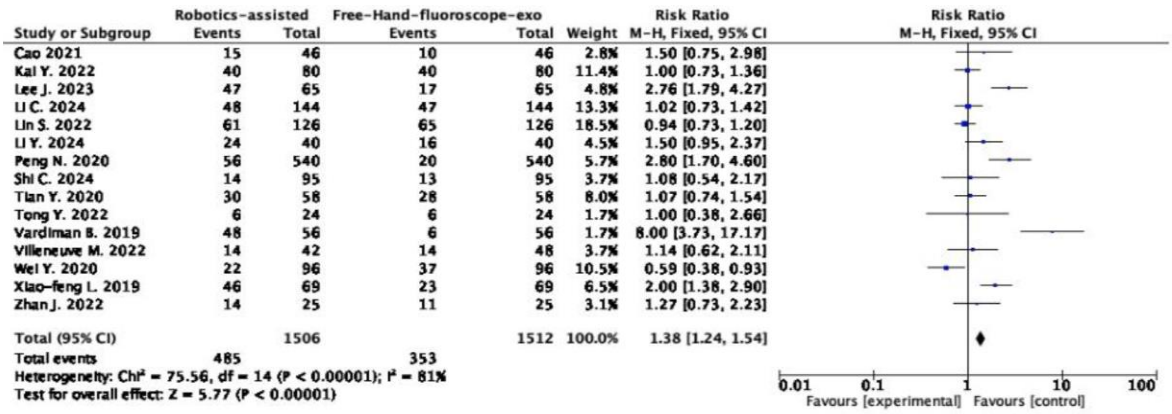


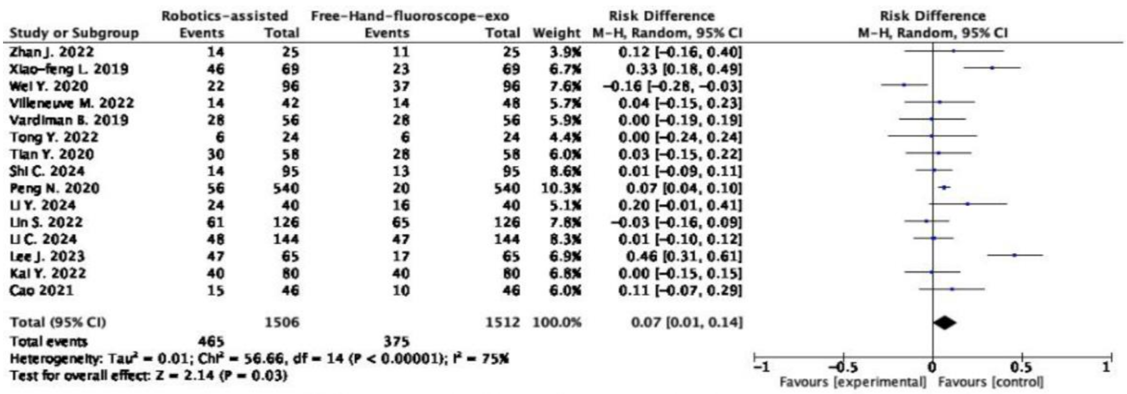
Figure 6. Funnel plot comparing studies of robotic-assisted and freehand pedicle screw placement



a) Florest plot; Odd Ratios: Robotics-assisted, Positional screw vs Free-Hand-fluoroscope



b) Florest plot; Risk-Ratio: Robotics-assisted, Positional screw vs Free-Hand-fluoroscope



c) Florest plot; Risk-difference; Robotics-assisted, Positional screw vs Free-Hand-fluoroscope

Figure 4. A) Forest plot comparing odds ratios for positional pedicle screw placement between robotic-assisted and conventional techniques; B) Forest plot comparing risk ratios for positional pedicle screw placement between robotic-assisted and conventional techniques; C) Forest plot showing risk differences in positional pedicle screw placement between robotic-assisted and conventional techniques

There was a total of 144 patients, with 92 in group A treated with robotic-assisted screw placement and 52 in group B treated with the freehand technique under fluoroscopic guidance. Group A subjects were then divided into 2 categories: the first group consisted of 48 patients for robotic-assisted navigation using an O-arm arch, and the second group consisted of 44 patients for robotic-assisted navigation with a C-arm arch using 3D imaging. The results showed that accuracy and safety are not always achieved because there was an overall failed pedicle screw placement rate of 3.7%, while 3.9% was observed in group A and 3.5% in subgroup 1. The concave misplacement rate was 5.1% with 5.2% in subgroup 1 and 5% in subgroup 2. The rates of convexity misplacement were 2.3% overall, 2.6% in subgroup 1, and 1.8% in subgroup 2, indicating the difficulty of placing pedicle screws in scoliosis patients (8-21). A 2024 retrospective study further assessed the placement accuracy of pedicle screws using the Gertzbein and Robbins classification, as well as clinical outcomes based on the Visual Analogue Scale (VAS), Japanese Orthopedic Association (JOA), and Oswestry Disability Index (ODI) scores (9). A total of 40 patients with ankylosing spondylitis and spinal fractures were included in the study and underwent surgery with a total of 341 pedicle screws implanted. Robotic-assisted surgery was performed in 16 patients with a total of 135 screws inserted, whereas in the 24 patients who had freehand fluoroscopic surgery a total of 206 screws were placed with direct vision based on spinal anatomical landmarks. There were no significant complications; minimal blood loss and shorter operating time was reported. Among the operated cases, robotic-assisted surgery scored the highest, with 129 out of 135 screws correctly placed compared with 182 out of 206 screws in the freehand group, further establishing the precision of robotic assistance in managing ankylosing spondylitis (9-22).

Discussion

This study showcases how far robotic-assisted spinal surgery has come, especially regarding the location of thoracolumbar fractures with no neurological changes needing decompression. Robotic technology has been applied to the development of certain minimally invasive procedures such as percutaneous reduction with internal fixation under fluoroscopy, thus improving the clinical results postoperatively (15, 27, 28). The 6 meta-analyses reviewed stated that robotic-assisted procedures led to a 16% decrease in incidence of postoperative complications due to inaccurately placed screws. Other studies have also stated that these robotic-assisted techniques outperformed or equaled the conventional freehand methods. Robotic-assisted placement of pedicle screws had a 33.3% accuracy according to an investigation, indicating robotic systems might serve as an excellent replacement for the traditional freehand technique of spinal fixation (16, 29, 30). Additional studies have reported that robot-assisted pedicle screw placement is associated with shorter operative times compared to navigation-based systems ($P < 0.05$) (17, 31, 32). Moreover, the sagittal and coronal angles of the pedicle have been identified as critical anatomical considerations in pedicle screw placement. The sagittal pedicle angle increases from 0° at T1 to 10° at T8, before decreasing back to 0° at T12. Meanwhile, in the coronal plane, pedicle angulation decreases from 10-15° at T1 to approximately 5° at T2, emphasizing the importance of precise screw trajectory in robotic-assisted procedures (33-36).

In a meta-analysis of 14 studies encompassing 1,723 patients and over 9,019 pedicle screws, the lowest screw malposition rates were achieved using robotic assistance with computer-navigated placement (5.4% compared with fluoroscopy-guided techniques at 15%), along with minimal intraoperative blood loss and fewer postoperative complications. Further corroboration comes from the more extensive review of 130 studies analyzing 37,337 pedicle screws showing 95.2% accuracy for navigation-guided screws and 90.3% for non-navigated screws (19, 37).

Robotic systems have been noted to also have lower rates of facet joint violations; this is particularly noticeable with the Renaissance system, which showed a 99% accuracy rate in which 960 screws were robotically placed and only 11 (1.1%) were malpositioned (20, 38). Robotic-assisted spine surgery improves precision in screw placement, minimizes radiation exposure, and improves fusion rates; thus, the general improvement of patient safety and outcomes is enhanced (18, 36).

However, with considerable advantages come limitations. A considerable challenge with robotic platforms is that they function under shared control, requiring continuous monitoring and active involvement of the surgeon throughout the procedure (39). Furthermore, cost issues remain a significant hindrance because the costs of robot-assisted procedures are considerably higher than that of conventional freehand techniques. Thus, whilst robotic guidance increases accuracy and clinical outcomes, the high economic burden of these systems may limit their broader introduction (40).

Limitations and Future Directions: Computer-assisted robotic navigation itself has been determined to hinge on the extent of the surgeon's proficiency alongside the new advances entered into the field of robotic systems. Moreover, some extensive preoperative preparation along with working knowledge of new technologies is prescribed. A lack of awareness or understanding of the Seo or Gertzbein and Robbins system could lead to violation of vertebrae, thus enhancing the importance of following these guidelines to avert vitiation of important vascular structures. However, the authors still maintained a consensus that robotic assistance brings about superior accuracy compared to freehand or fluoroscopically assisted techniques, which comes into play when (and if) denoting the very future of robotic surgery in more complex spinal procedures-such as in those that have followed vertebral fractures, spinal cord injuries or in the skills of microscopic reconstruction of anatomy in cases of traumatic events such as catastrophic car accidents. Furthermore, a future potential with augmented reality combined with robotic systems may further improve surgical outcomes. Hence, future pursuits to enhance robotic assistance will remain critical in placing this technology as a recognized sub-specialty in modern surgery.

Conclusion

The data examined here highlight the much greater accuracy and clinical effectiveness of robot-assisted spinal surgery in achieving between 60 and 90% accuracy in pedicle screw placement when compared practically to conventional freehand techniques. To maximize the accuracy of screw placement and minimize vertebral violations or violation of the spinal canal, the Seo classification and the Gertzbein and Robbins classification may be employed in practice.

Robot-assisted procedures have been shown to have close to negligible blood loss; however, the length of radiation exposure varies according to the skills and experience of the surgeon. A promising possibility has emerged whereby robot-assisted spinal surgery can be applied to cases of vertebroplasty, ankylosing spondylitis and vertebral fractures; thus, the utility of robotic technology in spinal surgery is being questioned.

As robotic systems continue to evolve, it may be expected that postoperative outcomes, complication rates, and rehabilitation will be substantially enhanced. Though high costs are linked to robotic surgery, the continuous progress is such that improves surgical precision, reduces complications, and hastens patient recovery.

Conflict of Interest

The authors declare no conflict of interest in this study.

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