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Review

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Clinical Indicators of Robotic Assisted versus Conventional Spine Surgery: A Systematic Review

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ABSTRACT

Background: Spine surgery has technological breakthrough of robotic assistance systems. The objective of this review is to explore clinical outcome indicators employed for comparison of outcomes of robotic assisted surgery to conventional spine surgery under the framework of evidence-based practice.

Subjects and Method: Based on guidelines issued by PRISMA, we systematically searched multiple sources, including PubMed, Scopus, and Science Direct databases. Studies comparing robotic assisted and conventional spine surgery were screened and analysed. Clinical indicators were collected and categorized according to surgical, functional, and safety concerns.

Results: The 24 review papers reviewed were all published during 2017 – 2025. The study design studies included three RCTs, nineteen RC studies, one prospective controlled study and one PSMC study pointing to the recent incorporation of robotic technologies in spinal surgery. This has revealed five categories of clinical indicators: accuracy benchmarks, operative parameters, safety and complications, functional outcomes, recovery and hospitalization. The most often reported indicator was the precision of the placement of the pedicle screw, followed by time of operation and intraoperative blood loss. Radiation exposure is a very important measure of occupational health and safety. The goal of this comprehensive clinical framework is to identify a method whereby an evidence-based clinical practice framework for efficient application of technological adoption becomes possible which is in favour of sustainable use can help to guide fiscally responsible adoption.

Conclusion: The current review establishes a composite framework of clinical indicators of clinical considerations towards robotic versus conventional spine surgery across robotic versus conventional spine surgery, a comprehensive evaluation paradigm. This framework provides a foundation upon which future studies can proceed.

Keywords: Robotic, conventional, spine surgery, clinical indicators.

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BACKGROUND

Over the last few decades, spinal surgery has experiences great change mainly driven by robotic assistance technology being adopted as part of surgical practice. The initial exploration of experimental navigation devices has evolved to state-of-the-art platforms that have superior precision, smaller variability and improved reproducing of various complex spinal procedures (Farber et al., 2021). The application of this technology also reflects trends in surgical medicine, as many subspecialities have increased calls to minimally invasive technique with computer assisted interventions (Lee et al., 2024).

Various devices and techniques are employed in robotic assisted spine surgery to enhance the surgeon's capabilities during the spinal procedures. Typically, robotic arm guidance, intraoperative navigation, and preoperative imaging support pedicle screw placement and other technical components in surgical guidance systems. the basic of robotic assistance in based on the translation of the previous three-dimensional planning of all surgical procedures into a precise physical process, preventing any human error and anatomical deviation (Farber et al., 2021). The TiRobot system, Mazor X Stealth Edition, TINAVI robot, Sanrobo, and ZhuZheng are some of the commonly mentioned platforms in the literature (Lai et al., 2025; Li et al., 2023; Liang et al., 2025; Wang et al., 2025; Wang et al., 2022).

On the other hand, freehand techniques in conventional spine surgery have been guided by fluoroscopic imaging (Alshaibi et al., 2025) or other intraoperative visualization techniques. It is well-known that surgeons operating autonomously based on anatomical landmarks, real-time radiographic information and experience optimize screw placement and surgical objectives (Franceschini et al., 2025).

Conventional methods demonstrated long-standing efficacy and safety but suffer from limitations arising from human variability, anatomical complexity, and technical requirements of minimally invasive exposure (Zhou et al., 2025). Distinguishing between these approaches offers an indication of the comparative evaluation of results used in current spine surgery research (Franceschini et al., 2025).

Patient safety has been a leading rationale for investigating robotic approaches in spine surgery (Zhou et al., 2025). Pedicle screw malposition and the associated vascular compromise, neurological damage, and revision surgery, commonly associated with conventional instrumentation, has been shown throughout studies (Farber et al., 2021). They hypothesize that the precision afforded by robotic systems may reduce these risks, as targeting accuracy and feedback may become more accurate and real time. Also the ergonomic benefits of surgical teams need to be accounted for, as a diminished radiation exposure of the intraoperative fluoroscopy is a significant occupational benefit for health care providers, which often practice various spinal operations (Park et al., 2020).

In addition to technical success, important managerial implications and safety profiles have been covered by the comparative analysis. Decision-makers must determine whether the substantial financial and operational costs of robotic platforms have been justified by safety improvements, improved surgical precision, and decreased occupational radiation. A comprehensive assessment of clinical out will be able to effectively tackle this issue by considering the operational efficacy as well as patient and group safety outcomes (Farber et al., 2021).

In robotic spine surgery, existing systematic reviews remain limited in scope, often limiting the population or surgical techniques examined. In addition, considerable heterogeneity remained regarding the clinical indicators evaluated throughout the study, inhibiting the formation of standard outcome measures. This systematic review addresses these limitations by covering all human populations and surgical techniques without limitations. In contrast to previous reviews, this study extracted a wide range of clinical indicator variabilities from comparative studies (RCT, RC, PSMC, and prospective controlled studies), to create a unified framework, rather than a straightforward comparative assessment.

SUBJECTS AND METHOD

1. Study Design

A systematic review was executed between February 3 and February 18, 2026. Literature research was conducted on February 3, 2026, utilizing three authoritative bibliographic databases: PubMed, Scopus, and Science Direct. Methodological transparency and reproducibility were ensured throughout the review process using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A systematic search strategy with PICO (Population, Intervention, Comparison, Outcome) framework was developed based on the target of the research question. To obtain a search with greater sensitivity and specificity, use of Medical Subject Headings (MeSH) vocabulary and keyword constructs was carried out. Use of Boolean operators (AND, OR) was handled strategically, and temporal and linguistic constraints were applied for greater search relevance (see Table 1).

Table 1. PICO framework

Population	No restrictions were imposed regarding patient demographics or clinical characteristics. The absence of population-specific eligibility criteria was deliberate, permitting the inclusion of studies encompassing patients across all age groups and representing the full spectrum of spinal pathologies without limitation.
Intervention	The intervention category comprised robotic-assisted spinal surgical procedures. Search constructs included: “robot” OR “robot-assisted” OR “robotic” OR “robots” AND “spine surgery” OR “pedicle” OR “lumbar” OR “thoracolumbar” OR “vertebral.” MeSH terms applied: Robotics AND (Pedicle Screws OR Lumbar Vertebrae OR Spinal Canal OR Hyperostosis, Diffuse Idiopathic Skeletal OR Spine).
Comparison	The comparator category encompassed conventional or non-robotic surgical techniques. Search constructs included: “spine surgery” OR “pedicle” OR “lumbar” OR “thoracolumbar” OR “vertebral” AND “conventional surgery” OR “traditional surgery” OR “fluoroscopy” OR “non-robotic surgery” OR “open surgery.” MeSH terms applied: Fluoroscopy AND (Pedicle Screws OR Lumbar Vertebrae OR Spinal Canal OR Hyperostosis, Diffuse Idiopathic Skeletal OR Spine).
Outcome	Primary outcome measures included clinical efficacy parameters. Search constructs included: “clinical outcomes” OR “clinical efficacy” OR “clinical effects.” MeSH terms applied: Clinical Trials as Topic OR Treatment Outcome.

2. Selection Criteria

All eligible studies should contain the following inclusion criteria: original research articles (in English) with full text accessible, comparison of robotic assisted spine surgery and conventional spine surgery techniques, clinical or surgical outcome measurement reporting, methodologically included studies must use comparative clinical outcomes criteria; randomized controlled trials; prospective or retrospective cohort studies. Only studies published in English will be eligible for global accessibility. The studies were published between the years 2017 and 2025, which indicates that the implementation of robotic practices in spinal surgery is still recent.

The exclusion criteria included study protocols without reported outcomes, cohort studies that did not include a conventional control group, and studies that demonstrated comparisons of two different robotic systems without having a conventional comparison arm. Limitations to this method include non-original research forms such as scoping or narrative reviews, systematic reviews, meta-analyses, case reports, uncontrolled case series analysis, expert statements and conference abstracts without full textual information. Studies that exclusively reported on technical descriptions without considering any clinical outcome data as well were also excluded from the final analysis.

3. Screening Process

Study selection was conducted by two separate investigators (first and second authors), during a two-stage evaluation process, including (1) screening for appropriateness in the initial stages of eligibility through titles and abstracts; (2) full-text review for final confirmation. Disputes were settled through conversation with a third investigator who served as an arbitrator. The PRISMA flow diagram was used to systematically document the selection process.

4. Risk of Bias Assessment

To strengthen methodological rigor, the risk of bias assessment was performed on all included studies to evaluate the quality of evidence and determine the extent to which each study addressed the possibility of bias in its design, conduct, and analysis.

The critical appraisal utilized the Joanna Briggs Institute (JBI) critical appraisal tools, specifically the JBI checklist for RCTs and Cohort studies. The assessment was performed independently by two investigators (HAS and IMESY) who subjected each paper to rigorous appraisal, with disagreements resolved by consultation with a third investigator (MB).

Analysis revealed two primary categories of methodological limitations. For the cohort studies, the most common issues cantered on the inadequate management of confounding variables and participant attrition. Specifically, a majority of studies either lacked or failed to report the use of statistical methods, such as multivariate regression analysis or advanced matching, to fully adjust for potential confounding variables or baseline differences. Furthermore, transparency regarding loss to follow-up was generally low. Most articles did not report the specific number of dropouts, the reasons for participant attrition, or the percentage of patients lost, and many failed to specify the use of appropriate statistical techniques (e.g., survival analysis, person-years at risk, or imputation) to manage unequal follow-up periods, censored observations, or missing data.

For the RCTs, the main limitation was the lack of blinding and unclear allocation concealment. All identified RCTs were judged to have a high risk of performance and detection bias because blinding of both participants and surgeons was deemed unfeasible due to the nature of the interventions, such as distinct surgical incisions for robot-assisted versus open surgery and the necessity for surgeons to utilize specific robotic workstations. Although randomization was reported, the articles consistently omitted or provided unclear details regarding the method of allocation concealment.

Despite these limitations, a common strength was noted across most studies, particularly within the cohort group, including the use of standardized inclusion criteria, comparable baseline groups, and independent, blinded outcome assessments (e.g., of radiological or functional outcomes). Based on the overall appraisal, all studies were ultimately deemed acceptable for "include" in the synthesis.

Table 2. Cohort Studies Critical Appraisal Tools

Authors	Year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Overall Appraisal
Hwang et al.	2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Include
Lai et al.	2025	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Include
		Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Include
Li et al.	2023	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
Li et al.	2025	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Unclear	Yes	Include
Liu et al.	2022	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
Seif et al.	2025	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
Tong et al.	2024	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Unclear	Yes	Include
Wang et al.	2025	Yes	Yes	Yes	Yes	No	Yes	Yes	Unclear	Yes	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Unclear	Yes	Unclear	Yes	Include
Zeng et al.	2025	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Unclear	Yes	Include
Zhan et al.	2022	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Unclear	Yes	Include
Fan et al.	2017	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	No	No	Yes	Include
Huang et al.	2025	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Include
Li et al.	2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	No	No	Yes	Include
Li et al.	2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Include
Li et al.	2023	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Include
Liang et al.	2025	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Include
Su et al.	2022	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Unclear	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Unclear	No	Yes	Include
Tao et al.	2024	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Yes	Yes	Include
		Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Unclear	Yes	Yes	Include
Wang et al.	2021	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Include
Wang et al.	2023	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Include

Authors	Year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Overall Appraisal
Wang et al.	2022	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	No	Yes	Include
		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	No	Yes	Include

Table 3. Critical Appraisal Tool for RCTs individual participants in parallel groups)

Authors	Year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Overall Appraisal
Cui et al.	2021	Yes	Unclear	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
		Yes	Unclear	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
Feng et al.	2020	Yes	Unclear	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
		Yes	Unclear	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
Feng et al.	2019	Yes	Unclear	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include
		Yes	Unclear	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Include

The methodological quality and risk of bias were assessed for all included studies using the critical appraisal tools specified in the JBI Manual for Evidence Synthesis, utilizing the JBI Critical Appraisal Tool for Cohort Studies and the JBI Critical Appraisal Tool for Randomized Controlled Trials (RCTs).

The risk of bias assessment was performed independently by two reviewers. Using the respective JBI tools (11 questions for Cohort Studies and 13 questions for RCTs), each reviewer systematically evaluated the studies, recording a judgment of “Yes,” “No,” or “Unclear” for each criterion. The “Comments” column was used to capture the specific methodological details that supported the judgment, facilitating subsequent comparison and consensus between the reviewers. The appraisal's primary objective was to evaluate the internal validity and methodological rigor of each study. A study was considered to have a higher risk of bias if key domains were marked as “No” or “Unclear,” especially concerning criteria related to controlling confounders, managing follow-up, or blinding. The final “Overall Appraisal” of “Include” for all studies indicates that while methodological flaws were identified, the studies possessed sufficient methodological quality and relevance to be integrated into the synthesis, thereby contributing to the review's transparency. These identified limitations are vital for informing the certainty of evidence assessment and for interpreting the results during the synthesis phase, such as by performing sensitivity analysis based on high-risk domains.

Analysis revealed two primary categories of methodological limitations. For the cohort studies, the most common issues centered on the inadequate management of confounding variables and participant attrition. Specifically, a majority of studies either lacked or failed to report the use of statistical methods, such as multivariate regression analysis or advanced matching (e.g., propensity score matching was used in only one study), to fully adjust for potential confounding variables or baseline differences. Furthermore, transparency regarding loss to follow-up was generally low. Most articles did not report the specific number of dropouts, the reasons for participant attrition, or the percentage of patients lost, and many failed to specify the use of appropriate statistical techniques (e.g., survival analysis, person-years at risk, or imputation) to manage unequal follow-up periods, censored observations, or missing data.

For the RCTs, the main limitation was the lack of blinding and unclear allocation concealment. All identified RCTs were judged to have a high risk of performance and detection bias because blinding of both participants and surgeons was deemed unfeasible due to the nature of the interventions, such as distinct surgical incisions for robot-assisted versus open surgery and the necessity for surgeons to utilize specific robotic workstations. Although randomization was reported, the articles consistently omitted or provided unclear details regarding the method of allocation concealment.

Despite these limitations, a common strength was noted across most studies, particularly within the cohort group, including the use of standardized inclusion criteria, comparable baseline groups, and independent, blinded outcome assessments (e.g., of radiological or functional outcomes). Based on their overall appraisal, all studies were ultimately deemed acceptable for "include" in the synthesis.

5. Data analysis

Data is extracted in the form of standard extraction instruments that result in data such as study characteristics (authorship, year of publication, methodology); the research objectives and key findings regarding clinical indicators. Data analysis was performed to report the list of clinical indicators together with the existing verifications.

6. Research Ethics

Given the absence of direct human subjects in this review, ethical approval was not necessitated.

RESULTS

The search yielded a total of 92 records across the three databases, with distribution as follows: PubMed contributed 53 records, Scopus contributed 35 records, and Science Direct contributed 4 records. The duplication search was performed using reference Mendeley. 64 records were screened for title and abstracts by two separate reviewers. In this phase, 19 studies were excluded due to missing criteria for inclusion after abstract review. The primary reasons for exclusion at this stage included absence of inappropriate study designs and comparative clinical outcomes.

Full-text assessment was performed on 45 reports sought for retrieval. Of these, 13 reports could not be retrieved due to full-text inaccessibility, leaving 32 reports for detailed eligibility assessment. The full-text screening resulted in the exclusion of 8 studies for the following reasons: full-text published in Mandarin language, comparison between two robotic surgery techniques without conventional control, study protocol without reported outcomes, cohort study without control group, combined robotic and freehand comparison without conventional fluoroscopy control, and cohort studies lacking appropriate conventional control groups. Finally, 24 articles will be analysed to generate a clinical indicator framework in robotic spine surgery (see Figure 1).

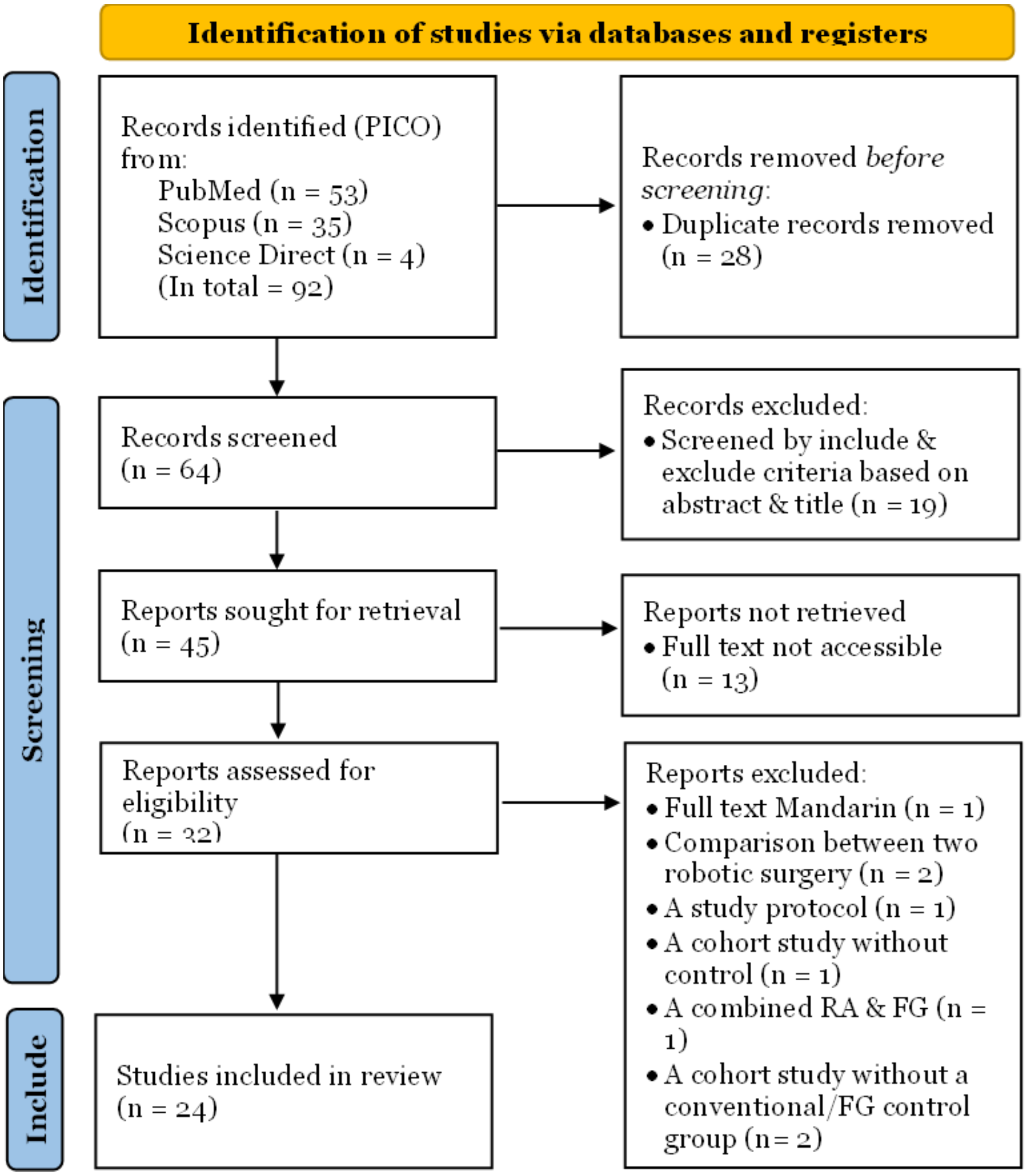

Figure 1. PRISMA flow chart of articles selection

1. Characteristics of Study

Twenty-four studies meeting the inclusion criteria were identified and included in the present review. Study designs included three randomized controlled trials, nineteen retrospective cohort studies, one prospective controlled study and one propensity score-matched cohort study.

Surgical procedures investigated across the included studies were diverse and included minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF), oblique lateral interbody fusion (OLIF), posterior lumbar interbody fusion (PLIF), percutaneous endoscopic lumbar discectomy (PELD), percutaneous vertebroplasty (PVP), percutaneous kyphoplasty (PKP), posterior cervical surgery, and various fracture fixation procedures.

Robotic systems employed across studies included the TiRobot, TINAVI, and Mazor X Stealth Edition, Sanrobo, ZhuZheng with or without navigation O-arm and C-arm, reflecting the technological diversity in this field. The comparator group used fluoroscopy-guided, freehand, open, and conventional surgical procedures found in the literature, providing a valid basis for evaluating differences in accuracy, safety, and overall clinical outcomes.

Table 4. Articles Synthesise Results

No.	Authors	Procedure	Objective	Clinical Indicators
1	Seif et al., 2025.	Pedicle screw insertion	To compare the accuracy and clinical outcomes of robot-assisted vs. conventional fluoroscopy-guided pedicle screw placements.	Screw accuracy (Gertzbein-Robbins scale), estimated blood loss, radiation exposure time, length of hospital stays (LOS), Macnab classification, VAS, and adverse events.
2	Fan et al., 2017.	Pedicle screw insertion	Compare accuracy and secondary outcomes of robot-assisted vs. other guided technologies (Navigation Template, O-arm Navigation, Fluoroscopy Guided).	Screw accuracy (Rampersaud A-D classification), deviation sagittal/ transversal, surgical time, total adverse events (dural tears, wound infection), fluoroscopy time per screw, blood loss, and postoperative stay.
3	Li et al., 2024.	Scoliosis Surgery	To compare robotic-assisted navigation (O-arm or 3D C-arm) vs. free-hand technique in scoliosis surgery.	Screw accuracy (AVR Grade 0-3), radiation exposure (patient and surgeon doses), operation time, blood loss, and apical vertebral rotation (AVR).
4	Wang et al., 2023.	S2 Screw Fixation	To evaluate safety, accuracy, efficiency and clinical outcome of robot-assisted S2 screw fixation.	Fluoroscopy times per screw, adjustment times per guide wire, screw position rating (excellent/good/ poor), and Majeed scores.
5	Liang et al., 2025.	Thoracolumbar Burst Fracture	Evaluate efficacy of ZhuZheng robot-assisted vs. C-arm fluoroscopy-guided PPSF for thoracolumbar burst fractures.	Screw placement accuracy Gertzbein-Robbins scale (Grades A+B), operative time, blood loss, fluoroscopy frequency, radiation dose, and VAS scores.
6	Li et al., 2023.	Thoracolumbar Fracture	Compare robot-assisted (RA) vs. fluoroscopy-guided (FG) pedicle screw fixation for thoracolumbar fractures.	One-time success rate (single attempt), accuracy (Gertzbein-Robbins scale), operative time, blood loss, VAS, and Cobb angle.
7	Feng et al., 2019.	Oblique Lateral Interbody Fusion (OLIF) pedicle screw insertion	Compare robot-assisted vs. fluoroscopy-assisted open pedicle screw insertion in elderly OLIF (Oblique Lateral Interbody Fusion) patients.	Accuracy of screw placement (modified Gertzbein-Robbins scale), operative time, pedicle screw placement time, radiation exposure to medical team, and intraoperative blood loss.

No.	Authors	Procedure	Objective	Clinical Indicators
8	Feng et al., 2020.	Pedicle screw insertion	Compare robot-assisted vs. freehand fluoroscopy-assisted lumbar pedicle screw insertion in osteoporotic patients.	Accuracy (Gertzbein-Robbins scale), operative time, blood loss, postoperative drainage, VAS (back/leg pain), ODI, and complication rates.
9	Huang et al., 2025.	Minimally Invasive Transforaminal Lumbar Interbody Fusion (MIS-TLIF)	Compare robot-assisted vs. fluoroscopy-guided MIS-TLIF for single-level lumbar degenerative diseases.	VAS scores (back/leg), ODI, operation time, radiation exposure time, hospital stay, pedicle screw placement accuracy (Gertzbein-Robbins scale), facet joint violation (FJV) rate, and complications.
10	Lai et al., 2025.	Percutaneous Vertebroplasty (PVP) in Thoracic Osteoporotic Vertebral Compression Fracture (T-OVCF)	Evaluate clinical efficacy and safety of TiRobot-assisted PVP surgery for middle/upper thoracic OVCF.	VAS and ODI scores, radiographic parameters (anterior height, kyphotic angle), operative time, blood loss, puncture frequency, fluoroscopy frequency, radiation exposure dose (surgeon and patient), bone cement leakage, and cement distribution.
11	Li et al., 2023.	Hangman Fracture	Compare efficacy of TINAVI robot-assisted vs. conventional open surgery for hangman fractures.	Screw placement accuracy (Rampersaud scale), invasion of adjacent facet joints, VAS, Neck Disability Index (NDI), SF-36, EQ-5D, operation time, blood loss, fluoroscopic dose, incision length, and hospital stay.
12	Li et al., 2025.	Single/Dual-Position Lateral Lumbar Interbody Fusion (LLIF)	Assess efficacy of robot-assisted single-position (SP) LLIF vs. traditional dual-position (DP) LLIF.	Operative duration, blood loss, fluoroscopy duration, screw fixation accuracy (Gertzbein-Robbins scale), VAS, ODI, SF-36 scores, Bridwell grade, and spinopelvic parameters (PT, SS, LL, SL, PI-LL).
13	Wang et al., 2025.	Atlantoaxial Fracture-Dislocation	To compare efficacy of traditional fluoroscopy-assisted and robot-assisted screw placement for atlantoaxial fracture-dislocation.	Surgical duration, intraoperative blood loss, hospital stay, screw placement accuracy (Gertzbein-Robbins scale), VAS, and JOA scores for cervical function.
14	Su et al., 2022.	Pedicle screw placement in posterior Cervical	To compare the accuracy and clinical outcomes of robot-assisted (RA) and fluoroscopy-guided (FG) pedicle screw placement in posterior cervical surgery.	One-time success rate, accuracy (Gertzbein-Robbins scale), operative time, radiation dose, radiation time, JOA scores, and NDI.

No.	Authors	Procedure	Objective	Clinical Indicators
15	Cui et al., 2021.	Transforaminal Lumbar Interbody Fusion (TLIF)	Compare robot-assisted MIS-TLIF vs. traditional open TLIF for lumbar spondylolisthesis.	Pedicle screw accuracy (Gertzbein-Robbins scale), duration of surgery, intraoperative blood loss, postoperative drainage, length of hospitalization, time to independent ambulation, VAS for back pain, ODI for function, and paraspinal muscle atrophy.
16	Zeng et al., 2025.	Percutaneous screw fixation for Lumbar Spondylolysis	To compare clinical efficacy between robot-assisted percutaneous screw fixation and conventional open screw fixation for lumbar spondylolysis.	Operative duration, blood loss, postoperative drainage, hospital stay, fluoroscopy times, radiation exposure dose, VAS, ODI, screw accuracy (Gertzbein-Robbins scale), and bone graft fusion rate (CT).
17	Tong et al., 2024.	Oblique Lateral Interbody Fusion (OLIF) pedicle screw insertion	To compare clinical efficacy and safety of navigation robot-assisted versus conventional OLIF with internal fixation.	VAS for back/leg pain, ODI, duration of surgery, blood loss, intraoperative fluoroscopy times, hospital stay, accuracy of pedicle screws (APS) Gertzbein-Robbins scale, and facet joint violation (FJV) rate.
18	Liu et al., 2022.	Unilateral UnstableSacral Fracture - Triangular Osteosynthesis (TOS)	To compare clinical efficacy of unilateral unstable sacral fractures involving the lumbosacral region treated with and without robot-aided triangular osteosynthesis.	Surgical bleeding, fluoroscopy time, operation time, fracture healing time, screw position (modified Gras criterion), residual displacement, Majeed score, and incision-related complications.
19	Li et al., 2024.	Posterior resection fusion and instrumentation (PRFI) Atlantoaxial for Atlantoaxial Dislocation with High-riding Vertebral Artery (AAD-HVA)	To compare robotic-assisted (RA) vs. fluoroscopic-guided free-hand (FH) techniques for atlantoaxial dislocation with a high-riding vertebral artery (AAD-HVA).	Screw accuracy (Gertzbein-Robbins scale), JOA score, VAS, NDI, blood loss, operative time, and radiation exposure dose.
20	Zhan et al., 2022.	C1/C2 screw placement in posterior atlantoaxial fusion.	To compare robotic assistance and conventional fluoroscopy for C1/C2 screw placement in posterior atlantoaxial fusion.	Estimated blood loss, surgical duration, radiation dosage, screw placement accuracy (Gertzbein-Robbins scale), JOA scores, VAS for neck pain, and fusion rate.

No.	Authors	Procedure	Objective	Clinical Indicators
21	Hwang et al., 2024.	Posterior Lumbar Interbody Fusion (PLIF)/Transforaminal Lumbar Interbody Fusion (TLIF)	To compare the accuracy of robotic spine surgery and conventional pedicle screw fixation in lumbar degenerative disease.	Screw accuracy (Gertzbein-Robbins scale and Babu classification for facet violation), radiological outcomes (adjacent segmental disease, mechanical failure), clinical outcomes (VAS, ODI), and operative time.
22	Wang et al., 2021.	Vertebroplasty in trating Osteoporotic Vertebral Compression Fracture (OVCF)	To assess radiation exposure and clinical efficacy of Tirobot-assisted vertebroplasty in treating OVCF.	Fluoroscopic frequency, operative duration, length of stay (LOS), cement leakage rates, Visual Analog Scale (VAS) score, JOA score, and Cobb's angle.
23	Wang et al., 2022.	Percutaneous Endoscopic Lumbar Discectomy (PELD)	To compare clinical outcomes of robot-assisted versus conventional fluoroscopy-guided percutaneous endoscopic lumbar discectomy.	Visual Analog Scale (VAS) for radiculopathy pain, Oswestry Disability Index (ODI), intraoperative blood loss, frequency of intraoperative fluoroscopy, MacNab classification, and complication rates.
24	Tao et al., 2024.	Bi/Uni-pedicular percutaneous kyphoplasty (PKP) in Osteoporotic Vertebral Compression Fracture (OVCF)	To compare bone cement distribution and clinical efficacy of robot-assisted PKP to fluoroscopy-assisted PKP for OVCFs.	Visual Analog Scale (VAS), Oswestry Disability Index (ODI), Cobb angle, anterior vertebral height, bone cement distribution patterns, operation time, and radiation dose.

2. Clinical Indicators Extraction

Twenty-four studies measured the effectiveness of RA with several variations in clinical indicators and operational definitions. Five main categories of clinical indicators were obtained: accuracy metrics, operating parameters, safety and complications, functional outcomes, recovery and hospitalization (see Table 5).

Table 5. Clinical Indicators

Clinical Indicators	Research	Included Reference
***Accuracy metrics**	24	
Pedicle screw placement	20	Seif et al.; Fan et al.; Li et al.; Wang et al. Liang et al.; Li et al.; Feng et al. (2019); Feng et al. (2020); Huang et al.; Li et al.; Li et al.; Wang et al.; Su et al.; Cui et al.; Zeng et al.; Tong et al.; Liu et al.; Li et al.; Zhan et al.; Hwang et al.
Accuracy precision (PVP, OVCV, PELD)	4	Lai et al.; Wang et al.; Wang et al.; Tao et al.
Facet joint violation rates	4	Huang et al.; Hwang et al.; Li et al.; Tong et al.
Intraoperative revision	4	Cui et al.; Feng et al.; Feng et al.; Fan et al.
Postoperative revision	13	Cui et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Li et al.; Seif et al.; Tong et al.; Su et al.;

Clinical Indicators	Research	Included Reference
		Liu et al.; Wang et al.; Wang et al.; Zeng et al.
Operative parameters		
Operative duration	23	Seif et al.; Fan et al.; Li et al.; Wang et al. Liang et al.; Li. et al.; Feng et al.; Feng et al.; Huang et al.; Li et al.; Li et al.; Wang et al.; Su et al.; Cui et al.; Zeng et al.; Tong et al.; Liu et al.; Li et al.; Zhan et al.; Hwang et al. Lai et al.; Wang et al.; Tao et al.
Intraoperative blood loss	21	Cui et al.; Feng et al.; Huang et al.; Feng et al.; Fan et al.; Li et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Tao et al.; Su et al.; Liu et al.; Zeng et al.; Wang et al.; Zhan et al.; Wang et al.
Postoperative drainage volume	3	Cui et al.; Feng et al.; Zeng et al.
Radiation Exposure	20	Feng et al.; Huang et al.; Feng et al.; Li et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Tao et al.; Su et al.; Liu et al.; Wang et al.; Wang et al.; Zeng et al.; Wang et al.; Zhan et al.
Complications		
Wound Infection	21	Cui et al.; Feng et al; Huang et al.; Fan et al.; Hwang et al.; Li et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Su et al.; Liu et al.; Wang et al.; Zeng et al.; Wang et al.; Zhan et al.; Wang et al.
Nerve root injuries	20	Cui et al.; Feng et al.; Huang et al.; Fan et al.; Hwang et al.; Li et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Tao et al.; Su et al.; Liu et al.; Wang et al.; Wang et al.; Wang et al.; Zhan et al.; Wang et al.
Dural tears	15	Cui et al.; Feng et al.; Huang et al.; Fan et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Su et al.; Wang et al.; Zhan et al.; Wang et al.
Hematoma	13	Cui et al.; Huang et al.; Fan et al.; Li et al.; Liang et al.; Li et al.; Lai et al.; Seif et al.; Su et al.; Liu et al.; Wang et al.; Zhan et al.; Wang et al.
Functional outcomes		
**Functional recovery	19	
ODI	11	Cui et al.; Feng et al.; Huang et al.; Hwang et al.; Li et al.; Li et al.; Lai et al.; Tong et al.; Tao et al.; Zeng et al.; Wang et al.
NDI	3	Li et al.; Li et al.; Su et al.
JOA	5	Wang et al.; Su et al.; Li et al.; Zhan et al.; Wang et al.
Majeed Pervic Score (MPS)	2	Wang et al.; Liu et al.
MacNab (Negative disc. exploration)	2	Seif et al.; Wang et al.

Clinical Indicators	Research	Included Reference
Pain intensity (VAS)	17	Cui et al.; Feng et al.; Huang et al.; Hwang et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Tao et al.; Wang et al.; Zeng et al.; Wang et al.; Wang et al.
Recovery and hospitalization		
Length of Stay	20	Cui et al.; Huang et al.; Feng et al.; Fan et al.; Hwang et al.; Li et al.; Li et al.; Li et al.; Liang et al.; Li et al.; Lai et al.; Seif et al.; Tong et al.; Su et al.; Liu et al.; Wang et al.; Zeng et al.; Wang et al.; Zhan et al.; Wang et al.

Japanese Orthopaedic Association (JOA); Oswestry Disability Index (ODI); Neck Disability Index (NDI); Visual Analogue Scale (VAS); Percutaneous Vertebroplasty (PVP); Percutaneous Endoscopic Lumbar Discectomy (PELD).

* Twenty-four studies employ accuracy metrics, divided into pedicle screw placement and precision only.

** A single study may employ multiple assessment instruments of functional recovery.

2.1 Accuracy Metrics

Recognition of clinical parameters found in the literature, as the placement of pedicular screw reported in 20 cases and corresponding studies on precision were reviewed (including precision in bone cement leakage and distribution such as those seen during percutaneous vertebroplasty (PVP) and percutaneous kyphoplasty (PKP), and puncture accuracy in percutaneous endoscopic lumbar discectomy (PELD): one of those was not mentioned (see Table 6).

Assessment of surgical precision of pedicel screw placement involved various standardized graded methodologies including the Gertzbein-Robbins scale (grades 0-3), modified Gertzbein-Robbins scale (grades A to E), Rampersaud classification system (grades A to D), and modified Grass criteria (grades 0-3). The instruments were used for quantitative measurement of screw position accuracy, including precision in screws, such as “Perfect” accuracy of placement (Grade A or zero deviation), “Clinically acceptable” score (grade of A+B or total scores of 0+1), or angular deviation measurements from sagittal plane or transverse plane. This methodology is intended to reduce data entry bias. Whereas AVR grading was based on post-operative vertebral rotation for scoliosis correction, demonstrating that the measurements are influenced by pathology-specific biomechanics as well as screw placement.

Relating scores of reported accuracy grading scales to instruments revealed a wide variety of scores depending on the surgical type employed and the anatomical vertebral level investigated. Arguing that such discrepancies existed in measurement methods, accuracy-related outcomes had become the prevailing standard in comparative studies when comparing robotic-assisted and conventional spinal surgery methods.

Other data utilized as accuracy measures included incidence rates of facet joint violation, presented in eight studies as the percentage of cases demonstrating unintended facet joint penetration, and screw malposition revision incidence rates, reported in four intraoperative context and four postoperative case studies. Such dimensions also help to illustrate a comparative aspect of comparison of precision between robotic and conventional surgical techniques.

Table 6. Accuracy Standard Grading Scales

Accuracy Standard Grading Scales	Acceptable measurable elements	Procedures	Reference
Gertzbein-Robbins scale (Grade A-D) in 14 studies	Grade 0: Screw in pedicle Grade 1: < 2 mm Grade 2: 2-4 mm Grade 3: > 4 mm	Pedicle screw insertion; Thoracolumbar Burst Fracture; Thoracolumbar Fracture; MIS-TLIF; LLIF; Atlantoaxial Fracture-Dislocation; TLIF; OLIF; PRFI; AAD-HVA; C1/C2 Posterior atlantoaxial fusion; PLIF	Seif et al.; Liang et al.; Li et al.; Feng et al. (2020); Huang et al.; Li et al.; Wang et al.; Su et al.; Cui et al.; Zeng et al.; Tong et al.; Li et al.; Zhan et al.; Hwang et al.
Modified Gertzbein-Robbins scale (A-E) in 1 study	Grade A: Screw completely within the pedicle (0 mm breach) Grade B: Breach ≤ 2 mm Grade C: Breach > 2 mm and ≤ 4 mm Grade D: Breach > 4 mm and ≤ 6 mm Grade E: Breach > 6 mm or screw completely outside the pedicle	Oblique Lateral Interbody Fusion (OLIF) pedicle screw insertion	Feng et al. (2019)
Rampersaud scale (Grade A-D) in 2 studies	Grade A: Screw placement is entirely within the pedicle cortex. Grade B: Screw placement is within 2 mm of the pedicle cortex. Grade C: Screw placement is within 4 mm of the pedicle cortex. Grade D: Screw placement is outside the pedicle cortex.	Pedicle screw insertion in lumbar degenerative disease, Hangman fracture	Fan et al.; Li et al.
Axial Vertebra Rotation (AVR) grade (0-3) in 1 study	Grade 0: both pedicle screw tips were visualized centrally between the two rods, vertebral rotation of 0°-8° Grade 1: one pedicle screw tip was obscured by the ipsilateral rod, vertebral rotation of 9°-12° Grade 2: one pedicle screw tip appeared lateral to the ipsilateral rod, vertebral	Scoliosis correction	Li et al.

Accuracy Standard Grading Scales	Acceptable measurable elements	Procedures	Reference
	rotation of >13°		
Modified Grass criteria in 1 study	Grade 0 (Ideal): Screw entirely within the pedicle with no cortical breach. Grade 1 (Minor Breach): Cortical breach <2 mm without clinical significance. Grade 2 (Moderate Breach): Breach 2–4 mm; potential risk to neural or vascular structures. Grade 3 (Severe Breach): Breach >4 mm; generally considered unsafe and may require revision.	Unilateral Unstable Sacral Fracture - Triangular Osteosynthesis (TOS)	Liu et al.
Intraoperative observation in 3 studies	Leakage and distribution of bone cements in	Percutaneous Vertebroplasty (2) and Kyphoplasty (1)	Lai et al.; Wang et al.; Tao et al.
Intraoperative observation in 1 study	“Excellent” or “Good” or “Poor”	S2 Screw Fixation	Wang et al.
Not specified	Puncture accuracy	Percutaneous Endoscopic Lumbar Discectomy (PELD)	Wang et al.

Minimally Invasive Transforaminal Lumbar Interbody Fusion (MIS-TLIF); Single/Dual-Position Lateral Lumbar Interbody Fusion (LLIF); Transforaminal Lumbar Interbody Fusion (TLIF); Oblique Lateral Interbody Fusion (OLIF); Posterior resection fusion and instrumentation (PRFI); Atlantoaxial for Atlantoaxial Dislocation with High-riding Vertebral Artery (AAD-HVA); Posterior atlantoaxial fusion; Posterior Lumbar Interbody Fusion (PLIF).

*Criteria “Perfect” (Grade A/0) and “Clinically acceptable” (Grade A+B or 0+1), as well as sagittal and transversal deviation in degrees.

2.2 Operative Parameters

Operative duration, blood loss, and radiation exposure turned out to be a common outcome variable which was extensively mentioned in the literature. One of these studies did so explicitly, while seven studies reported differing operational definitions of operative duration, and the rest provide no explicit specification. Intraoperative blood loss (in mL) was declared in eight studies as an explicit number, but the other published studies were not operational definitions. There had been no mention of measurement time limitation in postoperative drainage volume. Other important data were the number of cases of radiation exposure, which is a measure of occupational health impact of surgical personnel (see Table 7).

Radiation exposure quantification was heterogeneously distributed by four main dimensions. Radiation was evaluated by dose-based indicators milli-Gray (mGy) or milli-Sievert (mSv), temporal conditions (seconds, minutes), and number of fluoroscopic images or exposures for frequency counts (i.e. incidence and degree). Sixteen studies had combined the sum of radiation values reported for one procedure, whereas three studies normalized per screw inserted measurements. Radiation exposure was assessed for individual patients, surgeons or both by means of digital dosimeters, radiation meters, C-arm exported data. Temporal measurements were in seconds and minutes, and exposure measurements of dose were in mGy or mSv (see table 7).

Variable radiation dose measurement, adding further challenges for comparing studies. Taken together, the studies support that the formation of a unified radiation reporting regime combining actual dose (mGy or mSv) and fluoroscopy-related parameters would increase methodological transparency, provide a way to compare techniques and ultimately contribute to patient safety and safe operation for workplace protection in spine surgery.

Table 7. Operative Parameters

Operative Parameters	Definition	Surgical Procedure	Source
Operative time/ duration	Time to perform all procedures after anaesthesia, including positioning, exposure, instrumentation, fusion, closure, and changing position (After anaesthesia to Changing the patient's position (post-closure)/wound closure).	Minimally Invasive Transforaminal Lumbar Interbody Fusion	Cui et al.; Feng et al.
	Includes machine preparation time (assembly/calibration) into the total operative time.	Percutaneous screw fixation for Lumbar Spondylolysis	Zeng et al.
	Calculated from the patient's position and disinfection until the postoperative incision treatment is completed.	Percutaneous Vertebroplasty in the middle and upper thoracic osteoporotic vertebral compression fracture	Lai et al.
	Time from disinfection to closure.	Triangular osteosynthesis in unilateral unstable sacral fractures combined with lumbosacral junction injuries	Liu et al.
	Measured from the start of skin incision to the end of suturing.	Atlantoaxial fracture and dislocation	Wang et al.
	Overall operative time (from initial incision to application of surgical dressing)	Atlantoaxial dislocation in combination with high-riding vertebral artery	Li et al.
	Time taken to perform all surgical procedures including exposure of the operative area, laminectomy, diskectomy, fusion, and wound suture	Lumbar Pedicle Screw Internal Fixation in Patients with Osteoporosis	Feng et al.
Intraoperative blood loss	Sum of the fluid in the suction bottle and the amount of blood in the gauze	Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) for lumbar spondylolisthesis	Cui et al.
		Oblique lumbar interbody fusion (OLIF) with posterior pedicle screw fixation	Feng et al.

Operative Parameters	Definition	Surgical Procedure	Source
		Atlantoaxial dislocation with high-riding vertebral artery (AAD-HVA) fixation	Li et al.
		Lumbar pedicle screw internal fixation in patients with osteoporosis	Feng et al.
	Measured as the amount of blood in gauze	Percutaneous vertebroplasty (PVP) for middle and upper thoracic osteoporotic vertebral compression fractures	Lai et al.
	Estimated blood loss (mL)	Posterior C1 lateral mass and C2 pedicle screw fixation for atlantoaxial dislocation	Zhan et al.
		Thoracolumbar burst fracture percutaneous pedicle screw fixation (PPSF)	Liang et al.
		Atlantoaxial fracture and dislocation repair	Wang et al.
Post operative blood loss	Volume of blood lost after surgery, measured by the volume of fluid in the drainage bottle (mL)	Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) for lumbar spondylolisthesis	Cui et al.
		Oblique lumbar interbody fusion (OLIF) with posterior pedicle screw fixation	Feng et al.
		Atlantoaxial dislocation with high-riding vertebral artery (AAD-HVA) fixation	Li et al.
		Percutaneous screw fixation for lumbar spondylolysis	Zeng et al.
Radiation Exposure	Radiation dosage per screw (mGy) recorded by C-arm and exported by radiologist	Atlantoaxial dislocation with high-riding vertebral artery (AAD-HVA) fixation	Li et al.
	Cumulative radiation exposure of surgeons (mSv) measured by digital dosimeters; also recorded as number of fluoroscopic images	Lumbar pedicle screw internal fixation in patients with osteoporosis	Feng et al.
	Surgeon radiation exposure dose measured by dosi meter; Patient radiation exposure (mSv) from C-arm output	Percutaneous vertebroplasty (PVP) for middle and upper thoracic osteoporotic vertebral compression fractures	Lai et al.
	Radiation exposure for patient and surgeon measured using digital dosimeters	Scoliosis correction surgery (pedicle screw placement)	Li et al.
	Intraoperative radiation exposure dosage (mGy per screw)	Posterior C1 lateral mass and C2 pedicle screw fixation for atlantoaxial dislocation	Zhan et al.
	Radiation dose (mGy) and fluoroscopy frequency (times)	Thoracolumbar burst fracture percutaneous pedicle screw fixation (PPSF)	Liang et al.

Operative Parameters	Definition	Surgical Procedure	Source
	Intraoperative fluoroscopy times and cumulative radiation dose (mGy)	Percutaneous screw fixation for lumbar spondylolysis	Zeng et al.
		Percutaneous pedicle screw internal fixation for Levine-Edward type IIA hangman fractures	Li et al.
		Triangular osteosynthesis (TOS) for unilateral unstable sacral fractures	Liu et al.
		Oblique lateral lumbar interbody fusion (OLIF) for lumbar degenerative diseases	Tong et al.
	Radiation exposure time (seconds)	Pedicle screw placement for degenerative conditions or vertebral fractures	Seif et al.
	Fluoroscopy duration/time (seconds)	Single-position lateral lumbar interbody fusion (LLIF)	Li et al.
	Fluoroscopy time per screw (s)	Lumbar decompression or TLIF surgery	Fan et al.
	Total radiation exposure time (s) calculated as sum of cumulative time differences	Minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF)	Huang et al.
	Cumulative radiation time (minutes) and radiation dose (mSv)	Posterior cervical surgery (pedicle screw placement)	Su et al.
	Intraoperative radiation exposure dose (mGy)	Percutaneous kyphoplasty (PKP)	Tao et al.
	Frequency of intraoperative fluoroscopy (times)	Percutaneous endoscopic lumbar discectomy (PELD)	Wang et al.
	Mean times of fluoroscopy per screw	Posterior pelvic ring injury fixation (sacroiliac screw)	Wang et al.
	Fluoroscopic frequency (times)	Thoracolumbar osteoporotic compression fracture vertebroplasty	Wang et al.

2.3 Safety and Complications

Indicators of complications reported included wound infection rates in twenty-one studies, nerve root injuries in twenty studies, dural tears in fifteen studies, and hematoma formation in thirteen studies. These indicators are usually reported as the absolute number of cases in each study group, except for wound infection indicators. Wound infections are reported in 2 variants, absolute numbers and percentages.

Intraoperative revision for screw malposition represented a process indicator reflecting real-time accuracy assessment and correction during surgery. Post-operative revision rates provided longer-term outcome data regarding the clinical consequences of any accuracy deficiencies. Both indicators are reported as absolute numbers. However, the reviewed studies were not uniform in the measurement of this indicator, only 4 studies measured intraoperative indicators, and 13 studies measured postoperative revision.

Blood transfusion requirements offer additional safety metrics related to intra-operative blood loss and postoperative drainage that reflect surgical invasiveness. However, of all the studies reviewed, none reported this.

2.4 Functional Outcomes

Functional recovery indicators provided patient-centred outcome measures beyond technical surgical metrics in fourteen studies. The Oswestry Disability Index (ODI) appeared prominently in the reviewed literature as a validated measure of spinal functional status. Twelve studies reported ODI scores at multiple time points including preoperative baseline, immediate postoperative assessment, and longer-term follow-up at six months, one year, and beyond. This longitudinal reporting enabled assessment of functional recovery trajectories between surgical approaches.

Three studies implemented the Neck Disability Index (NDI) served as the functional assessment tool in studies involving cervical spine procedures. Five study implemented Japanese Orthopaedic Association (JOA) scores. Two studies that focused on Majeed scores in pelvic trauma (MPS) and two studies that classified negative disc exploration using MacNab classification provided further functional outcome measures in studies addressing spinal areas or pathological conditions. A single study may employ multiple assessment instruments of functional recovery. These diverse indicators showed the multi-dimensional characteristics of the evaluation of surgical outcomes in spine care. Eighteen studies assessed pain intensity based on the Visual Analog Scale (VAS), with studies reporting scores at preoperative, immediate postoperative, and follow-up time points (see Table 7).

2.5 Recovery and Hospitalization

Length of postoperative stay was one of the most important outcome measures used to report recovery, and this should matter for health care resource availability and patient experience. Length of stay in days was reported by twenty of the reviewed studies. Robotic and standard procedures were assessed and compared with one another with variations in response to individual procedures and institutional protocols. Postoperative drainage volume, when reported, gave additional information regarding surgical recovery as well as risk of developing complications. Early mobilization metrics and time to functional activities were generally not reported but emerged as supplementary recovery indicators.

DISCUSSION

In our review, the inclusion of 24 studies revealed considerable heterogeneity among study designs, surgical procedures, and robotic platforms. Accuracy was reported most consistently across studies with robotic support for improved precision of pedicle screws. These results are consistent with previous studies from large network meta-analyses that found robotic pedicle screw placement among the most accurate approaches relative to freehand or fluoroscopy-guided techniques (Farber et al., 2021; Zhang et al., 2020).

Additional constructs such as facet joint violation and revision rates were described in multiple studies; the concept of such metrics was echoed in previous systematic reviews in which robotic technologies were linked to a significantly decreased Facet Joint Violation (FJV) and lower odds of screw-related complications (Huang et al., 2025; Morello et al., 2025).

The data for operative duration, blood loss and radiation exposure were also reported inconsistently, frequently with variable operational definitions. These differences have also been reported in comparative TLIF meta-analyses in which robotics improved specific intraoperative parameters but not uniformly across studies (Guan et al., 2024; Maman et al., 2024).

Radiation exposure is also critical for patient safety and protecting labour forces and is quantified using differing doses and time-dependent measurement. This variability has been recognized previously in spinal radiation meta-analysis studies advocating for the standardization of dose reporting to better assess risk in the patient population and in surgical staff (Lee Young-Seok, 2024). However, increased evidence suggests that radiation time decreases and thus the robotic system can provide employment gains (Farber et al., 2021; Zhan et al., 2022).

Complication reporting is very variable, especially for wound infections, dural tears, hematomas, and nerve injuries, meta-analyses comparing robotic and traditional approaches have highlighted these inconsistencies. There are reports of robots decreasing complication rates among some researchers, while others do not find any significant differences after controlling for procedural heterogeneity and complexity (Guan et al., 2024; Morello et al., 2025). Apart from robotic comparisons, extensive SLRs for spinal surgery complications emphasise the fact that events such as dural tears significantly put victims at risk for postoperative infections, and therefore, the standardization of safety assessments is important (Duan et al., 2020; Huang et al., 2025).

Functional outcomes, including ODI, VAS, NDI, and JOA scores, were reported inconsistently across studies. This trend mirrors conclusions from recent MIS-TLIF SLRs, where robotic assistance improved intraoperative parameters but did not consistently outperform conventional methods in long-term functional recovery. Comparable findings emerged in an additional review of MIS procedures, suggesting functional improvements that are in line with stable postoperative recovery (Tan et al., 2016).

Postoperative hospitalization duration and drainage volume were reported in variability, due to differences in institutional protocols and surgical techniques. Similar variability has been a concern in previous reviews of robotic spine surgery, where long-term outcomes of hospitalization differed across types of procedures and healthcare settings (Maman et al., 2024; Morello et al., 2025).

Overall, improved accuracy and reduced fluoroscopy dependency are consistently associated with robotic systems. Inclusion criteria of clinical indicators in this SLR can provide an understanding of what indicators need to be standardized and can be used as a reference framework in occupational health and safety assessments.

This systematic review is limited by substantial heterogeneity across studies in design, patient populations, surgical techniques, and outcome measures, which restricts direct comparisons. Because most included studies are observational, they are susceptible to confounding and selection bias. Inconsistent definitions of screw accuracy, complication reporting, and operative metrics have limited synthesis.

Additionally, incomplete reporting of critical parameters and the risk of publication bias may compromise the comprehensiveness of the findings. Future studies should aim to standardized reporting frameworks, including uniform definitions of accuracy and complications. Higher quality prospective or randomized studies are needed to address bias and to clarify comparative effectiveness. It is important to report consistently operative parameters (e.g. radiation exposure, operative time, blood loss). Further long-term follow-up and cost-effectiveness analyses are needed to evaluate the broader clinical and economic impact of robotic-assisted spine surgery.

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AUTHORS' CONTRIBUTION

Conceptualization: HAS, MB; Data curation: HAS; Formal analysis: MB, HAS; Methodology: HAS, MB, IMESY; Visualization: HAS; Writing - original draft: HAS; Reviewer: IMESY, MB; Editing: HAS, MB; Supervision: MB.

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CONFLICT OF INTEREST

There are no conflicts of interest.

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