Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Robotic-Assisted Versus Conventional Pedicle Screw Fixation in Osteoporotic or Low-Bone-Mass Lumbar Degenerative Disease: A Systematic Review and Meta-Analysis of Screw Accuracy, Loosening, and Clinical Outcomes

Yu-cheng Wu
The First People's Hospital of Guangyuan
Pan Deng
The First People's Hospital of Guangyuan
Can Liu
The First People's Hospital of Guangyuan
Dong Zhao
The First People's Hospital of Guangyuan
Heng-zhi Guo
The First People's Hospital of Guangyuan
Zeng Wang
The First People's Hospital of Guangyuan
Xiao-bo Li
The First People's Hospital of Guangyuan
De-jian Xiang
The First People's Hospital of Guangyuan
Guan-jie Wei
The First People's Hospital of Guangyuan
Xiao-jun Huang
2277121665@qq.com

The First People's Hospital of Guangyuan

Research Article

Keywords: Robot surgery, Pedicle screws, Osteoporosis, Low bone mass, Lumbar degenerative disease, Meta-analysis

Posted Date: November 19th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11659970/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background

Osteoporosis and low bone mass reduce the holding power of pedicle screws, increasing the risks of screw malposition, loosening, and revision surgery after lumbar fusion. Robot assistance may improve screw trajectory execution, but quantitative evidence specific to this population is currently lacking.

Results

This study ultimately included 8 studies comprising 554 patients. All studies were conducted in China, including 2 randomized controlled trials and 6 retrospective controlled studies. Six studies involving 1,731 screws reported that the acceptable placement rate was 777/818 (95.0%) in the robot group versus 771/913 (84.4%) in the conventional group. The random-effects risk ratio (RR) was 1.12 (95% CI 1.08–1.15, I^2 = 4.1%), with a Hartung-Knapp adjusted 95% CI of 1.08–1.16. Three studies showed less facet joint violation in the robot group (45/488 vs. 135/528; RR 0.36, adjusted 95% CI 0.14–0.94, I^2 = 45.8%). Three studies indicated that the robot group had an average reduction in intraoperative blood loss of approximately 47 mL (Hartung-Knapp 95% CI − 85 to − 8 mL, I^2 = 68.8%), though heterogeneity was high.

Conclusion

Although the robot-guided pedicle screw implantation technique holds promise in improving the accuracy of single-screw implantation and reducing interference with the facet joints in the treatment of lumbar degenerative diseases for patients with osteoporosis or low bone mass, current research data do not provide sufficient evidence to confirm that this technique can effectively prevent postoperative screw loosening or optimize patient-reported functional scores. Therefore, before establishing it as a routine clinical protocol, more long-term controlled studies with patients as the unit of observation are still needed.

Introduction

Posterior spinal instrumentation and fusion remain a mainstream surgical approach for lumbar spinal stenosis, degenerative spondylolisthesis, or segmental instability that has failed to respond to conservative therapy. In patients with compromised bone quality, however, deterioration of trabecular microstructure and diminished bone mineral density weaken the screw-bone interface, thereby amplifying the risks of cortical breach, implant loosening, loss of corrective alignment, and subsequent revision procedures [1-3].

Contemporary robotic systems integrate preoperative trajectory design, intraoperative image registration, and mechanically stabilized guidance to refine screw placement. While prior systematic reviews have suggested that robot- or navigation-assisted techniques can enhance pedicle screw accuracy, these analyses have largely pooled heterogeneous cohorts—including trauma, tumor, deformity, and both normal-density and osteoporotic cases [4, 5]. Consequently, it remains uncertain whether such technological advantages can overcome the distinct biomechanical vulnerabilities of osteoporotic vertebrae.

Furthermore, osteoporosis introduces additional layers of complexity into surgical decision-making. Surgeons may resort to longer or larger-diameter screws, cement augmentation, cortical bone trajectory constructs, or more rigid fixation schemes; meanwhile, the robotic platform itself may alter surgical exposure, prolong or shorten operative

time, modify radiation exposure, and influence the rate of facet joint violation. Existing studies focusing on low-bone-mass populations are often limited by small sample sizes and inconsistent definitions of accuracy and loosening, underscoring the need for a dedicated synthesis before robotic assistance can be endorsed as a routine option for this vulnerable group.

Accordingly, this meta-analysis directly compares robot-assisted versus conventional pedicle screw fixation in adults with osteoporosis or low bone mass undergoing surgery for lumbar degenerative disorders. Prespecified outcomes include the proportion of acceptably placed screws, incidence of screw loosening, facet joint violation, perioperative burden, and patient-reported clinical results.

Methods

Protocol and Reporting

This systematic review was conducted in accordance with the PRISMA 2020 reporting guidelines [6]. The study protocol was prospectively registered with PROSPERO (registration number CRD42020261556099).

Eligibility Criteria

Studies were eligible for inclusion if they met all of the following conditions: (1) enrolled adult patients undergoing surgery for lumbar degenerative disorders who had osteoporosis, osteopenia, low bone mass, or quantitatively reduced bone mineral density; (2) compared robot-assisted pedicle screw placement with a conventional non-robotic technique; and (3) reported at least one relevant outcome, including screw accuracy, implant loosening, facet joint violation, perioperative parameters, or clinical scores. Both randomized and non-randomized controlled designs were considered.

We excluded single-arm studies, cadaveric or finite element model investigations, reviews, study protocols without results, and cohorts in which the primary pathology was fracture, infection, tumor, or vertebral augmentation. Studies where both treatment arms received robot-assisted screw placement were also ineligible, as such designs cannot yield a valid estimate of the effect of robotic assistance relative to conventional methods.

Information sources and search

PubMed, Embase, Cochrane, and the Chinese VIP database were searched from inception to 28 October 2026 without date or language restriction. PubMed yielded 23 records, Embase 62, CENTRAL 3, and VIP 961. Chinese records indexed by CNKI, Wanfang, and SinoMed were checked through database cross-links and publisher pages because independent search access to those platforms required authentication or CAPTCHA. All three CENTRAL records duplicated PubMed reports. The search combined robotic terms, pedicle-screw or spinal-fusion terms, osteoporosis or low-bone-mass terms, and lumbar degenerative terms. Subject headings and free-text fields were both used (Appendix A).

Study selection and data extraction

After deduplication, two reviewers independently screened titles, abstracts, and full texts against the eligibility criteria. Disagreements were resolved by discussion or a third reviewer. The reviewers independently extracted country, design, population, procedure, comparator, sample size, screw count, follow-up, accuracy definition, loosening, complications,

radiation, operative time, blood loss, and patient-reported outcomes, and cross-checked each entry against the source report. Study-selection results are reported below and in Fig. 1.

Outcomes

The primary radiographic outcome was the proportion of acceptable or Grade A pedicle screws after postoperative computed tomography. Secondary outcomes were screw loosening, facet-joint violation, intraoperative blood loss, operative time, radiation exposure, complications, and VAS or ODI outcomes.

Risk of bias and certainty

Non-randomized comparative studies were appraised with ROBINS-I [8] and randomized trials with RoB 2 [9]. Domains covered confounding, selection, intervention classification, missing data, outcome measurement, and selective reporting. GRADE was used to rate certainty for each pooled outcome [10].

Statistical analysis

For dichotomous outcomes—specifically screw placement accuracy and facet joint violation—we pooled risk ratios (RRs) with corresponding 95% confidence intervals, whereas continuous outcomes were summarized using mean differences. All RRs were analyzed on the natural logarithm scale to stabilize variance. A random-effects model was fitted using the DerSimonian–Laird estimator [11]. Because every meta-analysis included fewer than 15 studies, we additionally computed Hartung–Knapp–Sidik–Jonkman (HKSJ) adjusted confidence intervals to mitigate the spurious precision often associated with small-sample meta-analyses [12]. Between-study heterogeneity was quantified by τ^2 and I^2 statistics. Outcomes lacking usable event counts or denominators were excluded from pooling. Since each pooled analysis contained fewer than 10 studies, formal testing for small-study effects (e.g., Egger's test) was not undertaken. All statistical analyses were conducted in R version 4.5.2.

Results

Study selection

The searches identified 1,049 records (PubMed 23, Embase 62, CENTRAL 3, VIP 961). Sixty-four duplicates were removed, leaving 985 records for screening. After exclusion at title and abstract, 10 reports were sought and assessed. Two were excluded, leaving eight included studies (Fig. 1).

Study characteristics

The eight included studies enrolled 554 patients and were all conducted in China (Table 1). Two were randomized trials [13, 15] and six were retrospective comparative studies [14, 16–19, 21]. Given that the primary outcomes of this study were screw accuracy and related parameters, baseline demographic data such as patient age and sex were not included in the baseline table.

Table 1
Characteristics of included studies

Study	Country / design	Population	Robot intervention	Conventional comparator	Patients / screws	Follow-up	Reported outcomes
Feng 2019	China / RCT	Osteoporosis with lumbar disease	Robot-assisted pedicle screws	Freehand fluoroscopy	80 / 202 vs 225	NR	Accuracy, placement time, radiation, blood loss
Chen 2020	China / retrospective	Osteoporotic lumbar degenerative disease	Robot-assisted CBT screws	Manual CBT screws	58 / 116 vs 116	Mean 11.6 months	Accuracy, FJV, operative time, blood loss
Xie 2025	China / RCT	Osteoporotic lumbar spondylolisthesis	Robot-assisted double-threaded screws	Bone-cement-strengthened screws	80 / NR	12 months	Operative burden, FJV, VAS, ODI, SF-36, loosening
Zhong 2026	China / retrospective	Osteoporotic lumbar disease	Robot-assisted pedicle screws	Freehand pedicle screws	83 / 212 vs 208	NR	Grade A accuracy, FJV, screw length and trajectory
Xiong 2026	China / multicentre retrospective	Lumbar degenerative disease with low bone mass	AI-planned robot-assisted screws	Freehand screws	90 / NR	Mean 29.7 months	Grade A accuracy, loosening, fusion, VAS, ODI
Ma 2023	China / retrospective	Age > = 65 years with osteoporosis and lumbar degenerative disease	Robot-assisted CBT screws	Manual CBT screws	64 / 92 vs 164	NR	Accuracy, FJV, operative time, blood loss, hospital stay
Lin 2022	China / retrospective	Osteoporotic lumbar degenerative disease	Robot-assisted CBT screws	Manual fluoroscopic CBT screws	39 / 76 vs 80	3 and 6 months	Accuracy, operative time, fluoroscopy, blood loss, JOA
Yu 2024	China / retrospective	Primary osteoporosis and single-level unstable lumbar degenerative disease	Robot-assisted MIS-TLIF	C-arm fluoroscopy-assisted MIS-TLIF	60 / 120 vs 120	6 months	Accuracy, loosening, fusion, blood loss, fluoroscopy, VAS, ODI

CBT, cortical bone trajectory; FJV, facet-joint violation; NR, not reported; ODI, Oswestry Disability Index; RCT, randomized controlled trial; VAS, visual analog scale.

Risk of bias

Both randomized trials were rated as having some concerns [13, 15]. The six retrospective studies had serious overall risk of bias because of selection and unmeasured confounding (Table 2) [14, 16–19, 21].

Table 2
Risk-of-bias assessment

Study	Design	Confounding / randomization	Selection	Measurement	Overall
Feng 2019	RCT	Randomization stated; allocation details NR	Some concerns	Assessor blinding NR	Some concerns
Chen 2020	Retrospective	Serious confounding	Some concerns	Independent CT review	Serious
Xie 2025	RCT	Randomized; open procedural comparison	Some concerns	Assessor blinding NR	Some concerns
Zhong 2026	Retrospective	Serious confounding and combined planning	Some concerns	CT outcome; blinding NR	Serious
Xiong 2026	Retrospective	Serious confounding; AI plus robot intervention	Some concerns	CT outcome; blinding NR	Serious
Ma 2023	Retrospective	Serious confounding; treatment selection	Some concerns	CT outcome; blinding NR	Serious
Lin 2022	Retrospective	Serious confounding; treatment selection	Some concerns	CT outcome; blinding NR	Serious
Yu 2024	Retrospective	Serious confounding; treatment assigned by preference	Some concerns	CT outcome; blinding NR	Serious

Screw accuracy

Six studies contributed data on acceptable screw placement, covering 818 robot-assisted screws and 913 screws inserted using conventional techniques. The raw acceptable rates were 777 of 818 (95.0%) in the robotic group and 771 of 913 (84.4%) in the conventional group. Under a random-effects model (DerSimonian–Laird estimator), the pooled risk ratio for acceptable placement was 1.12 (95% CI 1.08–1.15), with minimal heterogeneity (I^2 = 4.1%). After Hartung–Knapp–Sidik–Jonkman adjustment, the 95% confidence interval became 1.08–1.16, which remained entirely above the null value of 1, indicating a statistically significant difference (Fig. 2). In leave-one-out sensitivity analyses, where each study was sequentially omitted, the resulting risk ratios ranged from 1.11 to 1.15; all corresponding adjusted intervals excluded unity.

Facet-joint violation

Three studies reported countable facet-joint violation. The pooled proportions were 45/488 (9.2%) in the robotic group and 135/528 (25.6%) in the conventional group. Robotic placement was associated with a lower risk of violation (RR 0.36, 95% CI 0.14–0.94; I^2=45.8%) (Fig. 3). Ma et al. also reported fewer head-side facet violations after robotic placement, but the difference was not significant and integer counts were not available in the abstract [18].

Screw loosening and complications

Screw loosening was not sufficiently reported for a conventional risk-ratio synthesis. Chen et al. observed no loosening in either 116-screw group over a mean follow-up of 11.6 months [14]. Yu et al. reported 7/120 loosened screws after robotic MIS-TLIF versus 18/120 after fluoroscopy-assisted MIS-TLIF at 6 months [21]. Yang et al. also reported no loosening over a mean 12.7 months, although that cohort was excluded because of probable overlap [20]. Xie and Xiong reported the outcome but not countable group data [15, 17].

Perioperative and clinical outcomes

Data on intraoperative blood loss were available from three studies encompassing 198 patients. The pooled random-effects mean difference was − 46.7 mL (95% CI − 59.0 to − 34.3; I^2 = 68.8%) (Fig. 4).

Beyond blood loss, the individual contributions of the included trials to perioperative and clinical endpoints were heterogeneous. Feng et al. observed shorter screw-insertion times and fewer fluoroscopic images in the robotic cohort, yet total operative duration did not differ significantly [13]. Chen et al. reported reductions in both operative time and blood loss under robotic guidance [14]. Zhong et al. found that finite-element-optimized robotic planning permitted the use of longer screws and wider transverse-plane angulation [16]. Xie et al. documented lower pain scores on postoperative day 3, shorter operative times, and reduced fluoroscopic exposure in the robotic group, with both arms showing within-group improvement in ODI and SF-36 [15]. At final follow-up, Xiong et al. reported superior VAS and ODI scores alongside earlier graft fusion in robot-treated patients [17]. Conversely, Ma et al. detected no between-group differences in blood loss, length of stay, or wound infection rate [18]; Lin et al. noted lower operative time, fluoroscopy frequency, and radiation dose with robotics, but comparable blood loss and JOA scores [19]; and Yu et al. reported less bleeding and fewer fluoroscopic shots with robotics, together with better early postoperative VAS and ODI, although these advantages had attenuated by the 3- and 6-month assessments [21].

Certainty of evidence

Certainty was low for screw accuracy and facet-joint violation and very low for blood loss and narrative clinical outcomes (Table 3). The main downgrades were confounding in retrospective studies, absence of assessor blinding, screw-level rather than patient-level analysis, inconsistency, and few studies.

Table 3
GRADE assessment of pooled or principal outcomes

Outcome	Studies / observations	Effect	I^2 or model	Certainty
Acceptable screw accuracy	6 studies / 1,731 screws	RR 1.12 (1.08–1.15); HK 1.08–1.16	I^2 4.1%	Low
Facet-joint violation	3 studies / 1,016 screws	RR 0.36; HK 0.14–0.94	I^2 45.8%	Low
Intraoperative blood loss	3 studies / 198 patients	MD -46.7 mL; HK -84.9 to -8.4 mL	I^2 68.8%	Very low
Screw loosening	Countable data in 2 studies; one double-zero	Narrative: 7/120 vs 18/120 in the informative study	Not pooled	Very low
VAS / ODI	Several studies with incomplete numeric reporting	Direction generally favored robotic placement	Not pooled	Very low

Discussion

In this meta-analysis focusing on patients with osteoporosis or low bone mass, robot-assisted pedicle screw placement significantly increased the proportion of acceptable screws and reduced the incidence of facet joint violation. Although statistical analysis confirmed reduced intraoperative blood loss in the robot-assisted group, substantial heterogeneity was observed across the included studies. Moreover, since surgeons rarely base their choice of surgical approach solely on minor differences in blood loss, this finding requires further validation. Limited by the number and quality of the included studies, the current pooled evidence is insufficient to confirm that robot-assisted screw placement can reduce the incidence of screw loosening or improve patient-reported outcomes.

A 2025 meta-analysis encompassing 22 studies and 2313 patients reported that robot-assisted lumbar interbody fusion improved the rate of perfect screw placement (OR 2.93, 95% CI 1.40–6.14) and reduced intraoperative blood loss, while operative time and overall complication rates did not differ significantly [22]. The direction of effect aligns with our findings, but that analysis incorporated fluoroscopy-guided and conventional navigation cohorts as comparators and did not restrict enrollment to individuals with osteoporosis or low bone mass. In contrast, our review adopts a narrower focus, thereby addressing a more specific clinical decision-making scenario.

Prior investigations have established that robotic navigation enhances pedicle screw accuracy and diminishes fluoroscopic radiation exposure for the surgeon, albeit often at the expense of prolonged overall operative duration [23]. These advantages are markedly operator-experience dependent: learning-curve data indicate that screw placement accuracy improves substantially after approximately 30 screw insertions, and robotic proficiency acquired by senior surgeons can be effectively transferred to junior trainees [24, 25]. Although no universal criteria exist for defining screw loosening, osteoporosis is uniformly acknowledged as a major risk factor regardless of the definition employed [26]. Consequently, while robotic technology can optimize screw trajectory, it cannot overcome the biomechanical deficits imposed by poor bone quality, nor can it eliminate the inherent risk of long-term screw loosening.

Work by McDonnell JM and colleagues suggests that robotic assistance yields clearer clinical value when screw placement is technically demanding and the surgical team has traversed the initial learning curve [24, 25]. A cost-utility analysis of MIS-TLIF indicated that robot-assisted surgery was cost-effective in 63% of probabilistic sensitivity simulations, although this conclusion was highly contingent on operating room and hospitalization cost parameters [27]. Therefore, the decision to adopt robotic assistance must be weighed against local reimbursement structures and equipment availability. Current evidence does not support the notion that robotic fixation alters the natural history of screw loosening in osteoporotic patients; surgical planning should additionally account for fluoroscopy resources, device accessibility, and individual surgeon experience.

Limitations

This meta-analysis has several methodological limitations. First, the accuracy analysis treated individual screws as the unit of observation, disregarding the within-patient clustering of screws; this independence assumption may have produced artificially narrow confidence intervals. Second, two included studies—Feng 2019 and Ma 2023—originated from the same institution with overlapping patient enrollment periods, although they examined different screw constructs (traditional pedicle screws versus cortical bone trajectory screws). Leave-one-out sensitivity analyses indicated that the overall effect estimates remained robust despite this overlap. Third, the included studies employed heterogeneous definitions of screw loosening, which limits the ability to directly compare findings with cohorts that applied alternative radiographic thresholds [26].

Conclusion

Robot-assisted pedicle screw fixation may improve screw-level accuracy and reduce facet-joint violation in osteoporotic or low-bone-mass lumbar degenerative disease. The certainty is low, and current evidence does not establish fewer screw-loosening events or better clinical outcomes. Longer-term, patient-level comparative studies are needed before robotic fixation can be recommended as a standard strategy for this population.

Declarations

Funding:

No specific funding was reported for this review.

Author Contribution

All authors contributed to the conception and revision of this manuscript. Data collection, analysis, and literature screening and exclusion were performed byWYC , DP and HXJ. The first draft of the manuscript was written by WYC; the remaining authors revised the draft and provided comments on previous versions.

References

1. Wang Y, Kahaer A, Maimaiti A et al (2023) Complication, fusion, and revision rate in the lumbar cortical bone trajectory and pedicle screw fixation techniques: a systematic review and meta-analysis. J Orthop Surg Res 18:382
2. Gertzbein SD, Robbins SE (1990) Accuracy of pedicular screw placement in vivo. Spine 15(1):11–14
3. Babu R, Park JG, Mehta AI et al (2012) Comparison of superior-level facet joint violations during open and percutaneous pedicle screw placement. Neurosurgery 71(5):962–970
4. Fatima N, Massaad E, Hadzipasic M, Shankar GM, Shin JH (2021) Safety and accuracy of robot-assisted placement of pedicle screws compared to conventional free-hand technique: a systematic review and meta-analysis. Spine J 21(2):181–192
5. Sturgill D, How J, Blajda T et al (2024) Are the clinical outcomes and cost-effectiveness of robot-assisted pedicle screw placement in lumbar fusion surgery superior to computed tomography navigation and freehand fluoroscopy-guided techniques? A systematic review and network meta-analysis. World Neurosurg 191:81–90
6. Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71
7. Zhao R, Fan Y, Qiao J, Ding L, Qu W, Fang X (2025) Robot-assisted cortical bone trajectory versus traditional pedicle screws in the treatment of lumbar spinal stenosis with osteoporosis: a retrospective cohort study. Asian J Surg 48(9):6062–6069
8. Sterne JAC, Hernan MA, Reeves BC et al (2016) ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ 355:i4919
9. Sterne JAC, Savovic J, Page MJ et al (2019) RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ 366:l4898
10. Guyatt GH, Oxman AD, Vist GE et al (2008) GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. BMJ 336(7650):924–926
11. DerSimonian R, Laird N (1986) Meta-analysis in clinical trials. Control Clin Trials 7(3):177–188
12. Higgins JPT, Thomas J, Chandler J et al (eds) (2024) Cochrane Handbook for Systematic Reviews of Interventions. Version 6.5. Cochrane
13. Feng S, Tian W, Sun Y, Liu Y, Wei Y (2019) Effect of robot-assisted surgery on lumbar pedicle screw internal fixation in patients with osteoporosis. World Neurosurg 125:e1057–e1062
14. Chen H, Liu S, Zhang J et al (2020) A comparative study on treatment of lumbar degenerative disease with osteoporosis by manual and robot-assisted cortical bone trajectory screws fixation. Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi 34(9):1142–1148

15. Xie B, Xu H, Deng H et al (2025) The therapeutic effect of robot-assisted double-threaded pedicle screws in the treatment of osteoporotic lumbar spondylolisthesis. J Orthop Surg (Hong Kong) 33(3):10225536251392628
16. Zhong C, Han Z (2026) Biomechanical optimization of pedicle screw trajectories in osteoporotic lumbar fusion: finite element analysis and validation of robotic-assisted implementation. J Robot Surg 20(1):99
17. Xiong X, Chen W, Ma C et al (2026) AI-planned and robotic-assisted pedicle screw placement improves accuracy and reduces loosening in lumbar fusion for patients with low bone mass: a multicenter study. Eur J Orthop Surg Traumatol 36(1):243
18. Ma S, Liu B, Li N, He D (2023) Comparison of robot-assisted and conventional manual placement of cortical bone trajectory screws in elderly patients with osteoporosis undergoing lumbar spine surgery. Chin J Tissue Eng Res 27(27):4332–4336
19. Lin S, Hu J, Wan L, Tang L, Wang Y, Yu Y (2022) Robot-assisted cortical bone trajectory screw fixation for lumbar degenerative disease. Chin J Tissue Eng Res 26(15):2356–2360
20. Yang L, Duan Y, Hao D et al (2025) Comparative study of Renaissance robot-assisted cortical bone screws in lumbar fixation for patients with osteoporosis. J Cervicodynia Lumbodynia 46(1):143–149
21. Yu J (2024) Clinical study of robot-assisted posterior pedicle screw placement for lumbar degenerative disease in older patients with osteoporosis [master's thesis]. Fuzhou: Fujian Medical University
22. Ardila CM, Angel-Estrada S, Gonzalez-Arroyave D (2025) Robot-assisted vs conventional lumbar interbody fusion: a systematic review and meta-analysis of perioperative, radiographic, and clinical outcomes. World J Orthop 16(11):110276. 10.5312/wjo.v16.i11.110276
23. Zhang Q, Han XG, Xu YF et al (2020) Robotic navigation during spine surgery. Expert Rev Med Devices 17(1):27–32. 10.1080/17434440.2020.1699405
24. McDonnell JM, Ahern DP, Doinn O (2020) Surgeon proficiency in robot-assisted spine surgery. Bone Joint J 102–B(5):568–572. 10.1302/0301-620X.102B5.BJJ-2019-1392.R2
25. Siddiqui MI, Wallace DJ, Salazar LM, Vardiman AB (2019) Robot-assisted pedicle screw placement: learning curve experience. World Neurosurg 130:e417–e422. 10.1016/j.wneu.2019.06.107
26. Marie-Hardy L, Pascal-Moussellard H, Barnaba A et al (2020) Screw loosening in posterior spine fusion: prevalence and risk factors. Global Spine J 10(5):598–602. 10.1177/2192568219864341
27. Garcia D, Akinduro OO, De Biase G et al (2022) Robotic-assisted vs nonrobotic-assisted minimally invasive transforaminal lumbar interbody fusion: a cost-utility analysis. Neurosurgery 90(2):192–198. 10.1227/NEU.0000000000001779

Figures

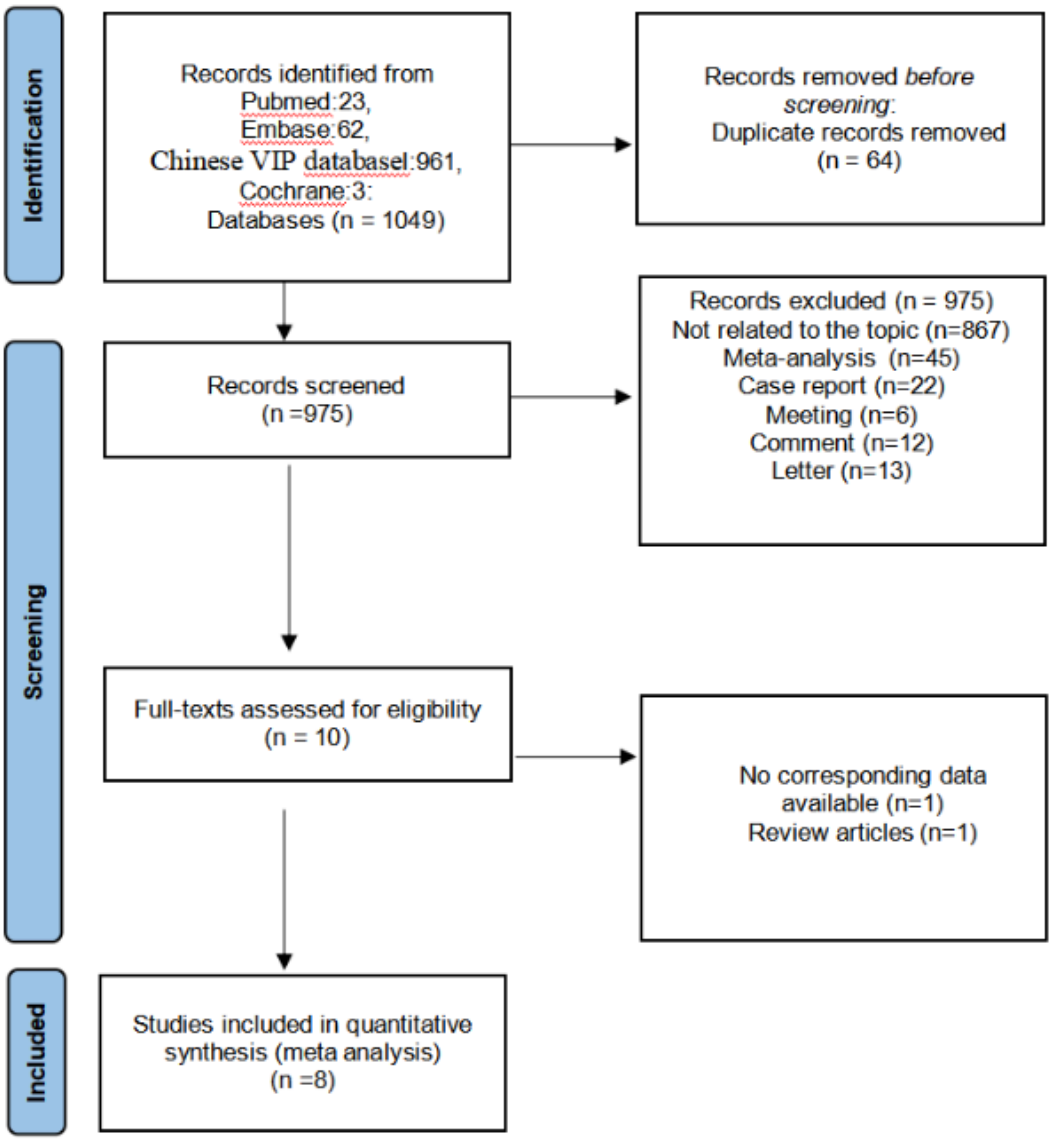


Figure 1

PRISMA 2020 flow of records and included studies.

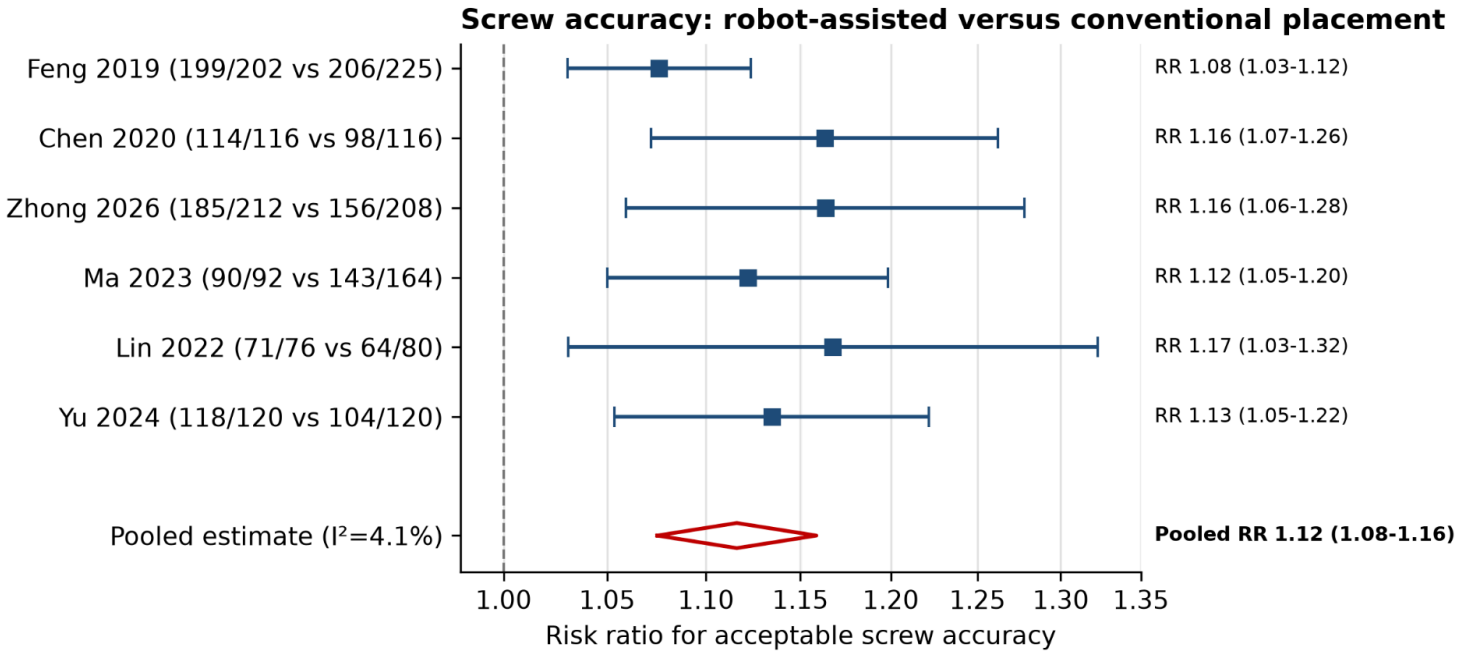


Figure 2

Forest plot of acceptable screw-level placement. The diamond uses the Hartung-Knapp adjusted confidence interval; study-level intervals are conventional 95% confidence intervals.

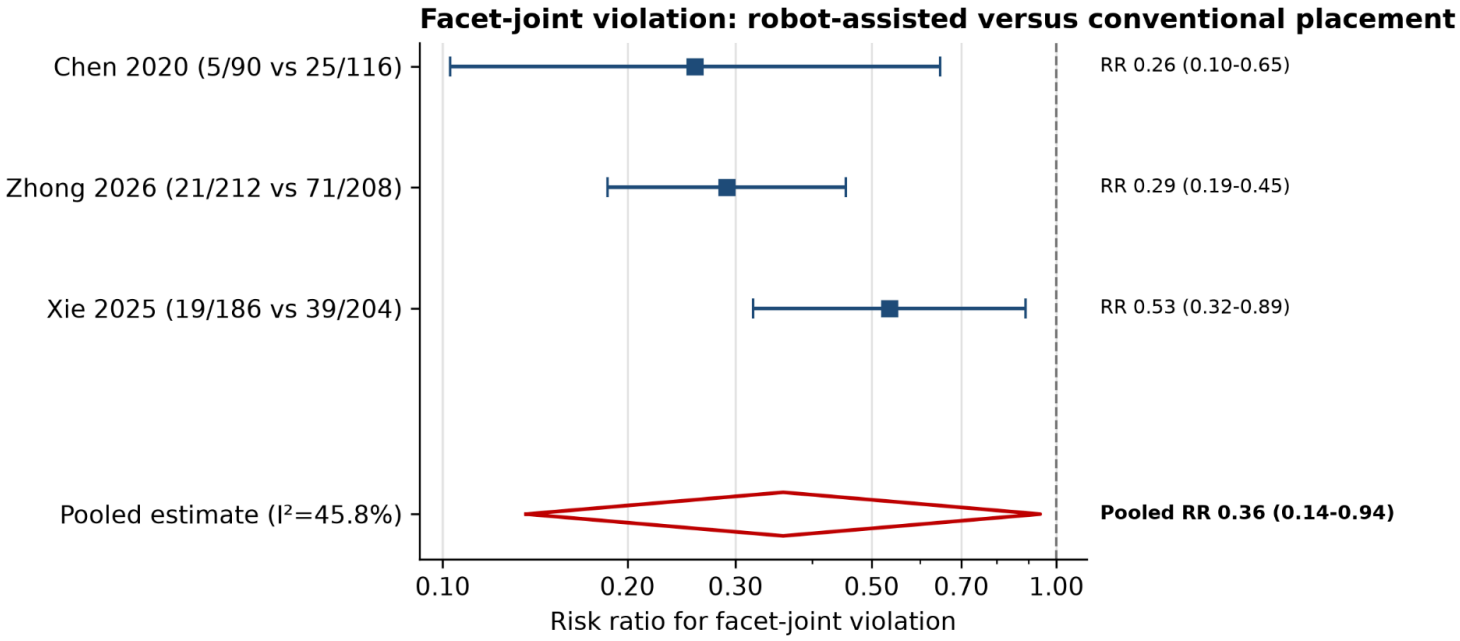


Figure 3

Forest plot of facet-joint violation. The pooled estimate uses the Hartung-Knapp adjusted confidence interval.

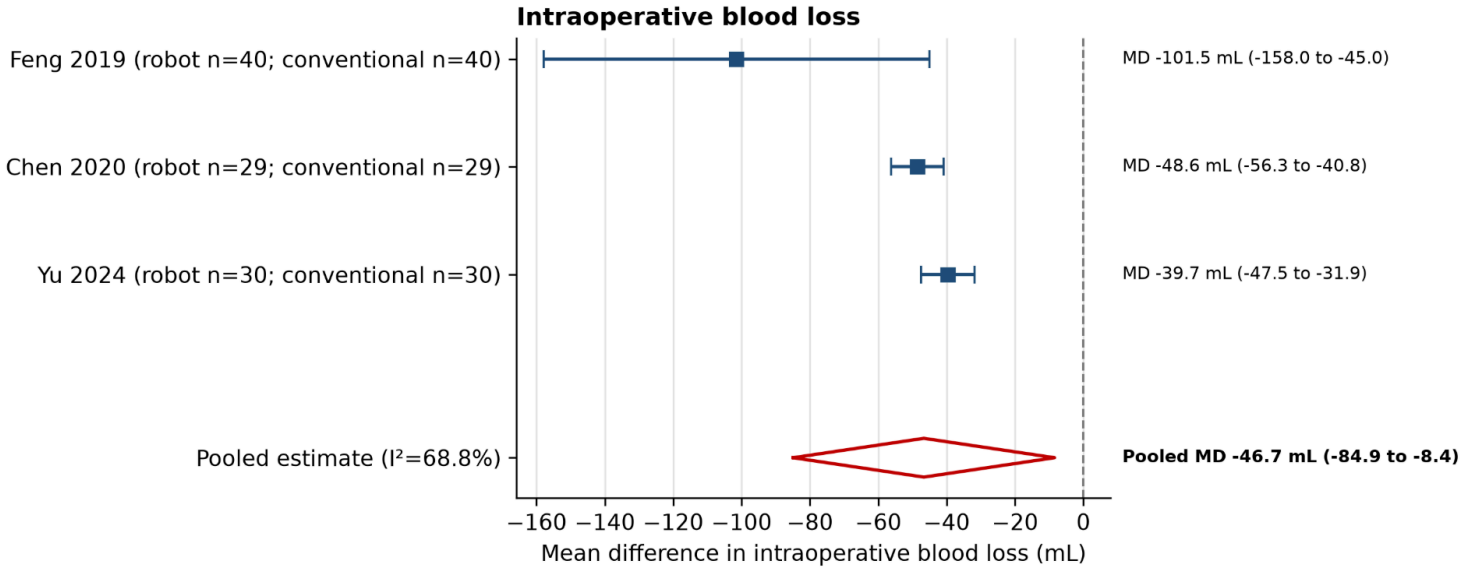


Figure 4

Forest plot of intraoperative blood loss. The Hartung-Knapp pooled interval excludes no difference but remains imprecise.