# Association of robot-assisted techniques with the accuracy rates of pedicle screw placement: A network pooling analysis

Fei-Long Wei,[1] Quan-You Gao,[1] Wei Heng,[1] Kai-Long Zhu, Fan Yang, Rui-Ming Du, Cheng-Pei Zhou,* Ji-Xian Qian,* and Xiao-Dong Yan *

Department of Orthopaedics, Tangdu Hospital, Fourth Military Medical University, 569 Xinsi Road, Xi'an 710038, China

eClinicalMedicine
2022;48: 101421
Published online xxx
https://doi.org/10.1016/j.eclinm.2022.101421

## Summary

**Background** Traditional paired meta-analyses have yielded inconsistent results for the safety and effectiveness of robotic-assisted pedicle screw placement due to the high heterogeneity within studies. This study evaluated the clinical effectiveness and safety of robotic-assisted pedicle screw placement.

**Methods** The Embase, PubMed, and Cochrane Library databases were searched with no language limitations from inception to Jan 4, 2022. Odds ratio (OR), mean difference (MD), and 95% confidence interval (CI) were used to report results. The main outcomes were accuracy of pedicle screw placement, proximal facet joint violation, and complications. The study protocol was published in PROSPERO (CRD42022301417).

**Findings** 26 trials including 2046 participants evaluating robotic-assisted pedicle screw placement were included in this study. Our pooled results showed that Renaissance (OR 2.86; [95% CI 1.79 to 4.57]) and TiRobot (OR 3.10; [95% CI 2.19 to 4.40]) yielded higher rates of perfect pedicle screw insertion (Grades A) than the conventional freehand technique. Renaissance (OR 2.82; [95% CI 1.51 to 5.25]) and TiRobot (OR 4.58; [95% CI 2.65 to 7.89]) yielded higher rates of clinically acceptable pedicle screw insertion (Grades A+B). However, ROSA, SpineAssist, and Orthobot were not associated with higher perfect pedicle screw insertion and clinically acceptable pedicle screw insertion rates. Robot-assisted techniques were associated with low rates of proximal facet joint violation (OR 0.18; [95% CI 0.10 to 0.32]; $I^2$:9.55%) and overall complications (OR 0.38; [95% CI 0.23 to 0.63]; $I^2$:27.05%). Moreover, robot-assisted techniques were associated with lower radiation doses (MD −14.38; [95% CI −25.62 to −3.13]; $I^2$:100.00%).

**Interpretation** Our findings suggest that only Renaissance and TiRobot systems are associated with high accuracy rates of pedicle screw placement. Robotic-assisted techniques hold great promise in spinal surgery due to their safety and effectiveness.

**Funding** This work was supported by grants from the National Natural Science Foundation of China (No. 81871818), Tangdu Hospital Seed Talent Program (Fei-Long Wei) and Natural Science Basic Research Plan in Shaanxi Province of China (No.2019JM-265).



**Keywords:** Artificial intelligence; Accuracy; Safety; Cervical spinal surgery; Robot-assist

## Introduction

The pedicle screw technique represents a major breakthrough in spinal surgery, widely used for spinal stabilisation in posterior lumbar fusion. Accurate screw placement is critical to avoid damage to adjacent neural structures and blood vessels due to their proximity to the spinal canal and surrounding blood vessels.[1] Traditional internal fixation procedures, using freehand tools, were based on anatomical landmarks and intraoperative fluoroscopic images that require an experienced surgeon to ensure the accurate placement of the screw.[2] It is widely acknowledged that in lumbar spine revision surgery, the normal anatomical structure is often disrupted due to previous operations, further increasing risks during surgery.[3] In such cases, complications

*Corresponding authors.
*E-mail addresses:* flweispine@fmmu.edu.cn, feilongspine@163.com (F.-L. Wei), xdyan8068@163.com (X.-D. Yan), pasmiss2012@163.com (J.-X. Qian), zhoucpei@126.com (C.-P. Zhou).

[1] The authors contributed equally to this work.

## Research in context

*Evidence before this study*

Accurate screw placement is critical to avoid damage to adjacent neural structures and blood vessels due to their proximity to the spinal canal and surrounding blood vessels. PubMed, Embase, and Cochrane Library databases were searched without language restrictions from inception to Jan 4, 2022 using terms "spine", "robotics" and related. Prior meta-analyses that compared the robotic-assisted pedicle screw insertion technique with the conventional technique yielded inconsistent conclusions given the heterogeneity among the included studies.

*Added value of this study*

Results of our study suggest that Renaissance and TiRobot systems are associated with high accuracy rates of pedicle screw placement. Robotic-assisted techniques hold great promise in spinal surgery given their safety and effectiveness.

*Implications of all the available evidence*

Our findings substantiate that robotic-assisted techniques have huge prospects for clinical application to assist doctors in placing pedicle screws safely and effectively. This work will provide support for the further development of robotic-assisted techniques.

related to pedicle screw placement are not uncommon.[4,5] Moreover, in recent years, a computer-aided system has been developed to significantly improve the accuracy of screw placement.[6,7] Robotic system represent a new technology with high inherent precision and stability.[8]

The first spinal robot was approved by the US FDA in 2004.[9] Since then, continuous innovation in surgical robotics has driven the development of modern spine surgery.[10] With the advent of new robotic navigation technologies, robotic surgery has experienced significant expansion in recent years due to its high precision and stability.[11] SpineAssist is a spine-mounted robot that improves screw positioning accuracy and reduces intraoperative radiation exposure.[12] The Renaissance® is the Mazor's second-generation spine robot, replacing the SpineAssist in 2011.[9] Although the two robots are similar in platform installation and robotic arms, the Renaissance robot has improved software and hardware, with upgraded image recognition algorithms.[9,13] Importantly, ROSA utilises a robotic arm and navigation camera, allowing real-time adjustment of the robot trajectories.[14] TiRobot is the first orthopaedic surgical robot developed in China, possessing a robotic arm with tracking capabilities and has an integrated intraoperative 3D navigation system.[15,16] Finally, Orthbot is a novel spinal robotic system with automatic drilling power that has been introduced recently.[11]

A growing body of research has demonstrated that the robotic-assisted technique has higher accuracy rates than the conventional freehand technique.[3,17-20] Two prospective, randomized controlled trials (RCTs) have shown that robotic-assisted pedicle fixation is as accurate as the freehand technique.[21,22] In contrast, Ringel et al. reported that the accuracy of the conventional freehand technique was superior to the robotic-assisted technique.[22] The robotic-assisted pedicle screw insertion technique has been compared with the conventional technique in meta-analyses yielding inconsistent conclusions.[2,8,10] Although significant heterogeneity was present within the results, the source of the heterogeneity was not explored in most studies. We hypothesized that the pooled estimates in these studies were inaccurate due to the large range of robotic-assisted systems used. Accordingly, the present study sought to compare the accuracy of different robotic systems during pedicle screw placement.

## Methods

### Search strategy and selection criteria

The Cochrane and PROSPERO databases were independently searched by two reviewers (F.L.W. and Q. Y.G.) to avoid duplicates. The Embase, PubMed, and Cochrane Library databases were searched with no language limitations from inception to Jan 4, 2022. The search strategy is provided in detail in Supplementary Table 1. After the preliminary screening of titles or abstracts, two independent reviewers (F.L.W. and Q.Y.G.) evaluated related publications. The study protocol was published in PROSPERO (CRD42022301417). The studies were screened according to the PICOS criteria. The selection criteria are provided in detail in Supplementary Table 2.

### Data extraction and outcomes

Two independent reviewers (F.L.W. and Q.Y.G.) extracted data from the included articles, including characteristics of investigators, type of study, surgical methods, pedicle screws, characteristics of participants, robot type, indications and main outcomes. Disagreements between the two investigators were resolved by discussing with a third investigator (W. H.). The primary outcomes were accuracy of pedicle-screw placement assessed by the Gertzbin-Robbin Classification,[23] proximal joint facet violation, and complications. The secondary outcomes were operative time, radiation time, and radiation dose.

### Quality and risk-of-bias assessment

The Cochrane Collaboration's tool for assessing the risk of bias[24] was used by two reviewers (F.-L.W. and Q.-Y. G.) to independently evaluate the included RCTs for potential bias. The detailed information on the tool for assessing the risk of bias is provided in Supplementary Table 3. The overall risk of bias was divided into "high risk," "low risk," or "unclear risk". The Newcastle-Ottawa Quality Assessment Scale (NOS)[25] was used to evaluate the quality of the included cohort studies (Supplementary Table 4). A high-quality study was associated with a NOS score > 6. Disagreements between the two investigators were resolved by discussing with a third investigator (W. H.).

### Data analysis

First, a random-effects model was used for pairwise analysis to pool odds ratio (OR) and 95% confidence interval (CI) for categorical data. A *P*-value <0.05 was statistically significant. The heterogeneity statistic $y^2$ was used to assess heterogeneity among studies.[26] We found significant heterogeneity among studies for the accuracy of pedicle screw placement ($y^2 > 50$). Accordingly, we performed network meta-analyses in software STATA using a frequentist consistency model to compare the accuracy of pedicle screw placement of different robotic systems. It is well-established that good consistency is the key to reliable results, characterized by consistency between direct (meta-analysis results) and indirect results (network meta-analysis results). Moreover, the indirect results were compared with the pairwise direct results to analyze the source of inconsistency.[27] Network meta-analysis results were presented as ladder diagrams. At the same time, each intervention was internally ranked, and the surface under the cumulative ranking curve (SUCRA) probability was drawn. The accuracy rates of the interventions were ranked by comparing the SUCRA values, which range from 0% to 100%. A higher SUCRA value corresponded to a higher ranking and higher accuracy rates in each comparison. Continuous data were analyzed using the pooled mean difference (MD). Network meta-analysis was not conducted for the secondary outcomes due to the small number of reported studies. Moreover, subgroup analysis was conducted to explore the source of heterogeneity. Egger's test was performed to evaluate for publication bias. All data were analyzed by STATA 16.0 (Stata Corp, College Station, TX, USA).

### Ethics statement

Ethical approval for this study is not applicable as the data used were collected from previously published research in the literature. All the included studies in this study had received ethical approval prior to data collection.


### Role of the funding source

The funding body had no role in the design of the study, data collection, analysis, interpretation or in writing the manuscript. All authors had full access to all the data in the study, and accept responsibility to submit for publication.


## Results

### A systematic review and qualitative assessment

The flow diagram in Figure 1 shows the patient selection process, with inclusion and exclusion criteria. 2046 participants (male: 46.22%; female: 53.78%) were included from 26 trials,[3,5,11–14,16,17–19,21,22,28,29–40,41] conducted in China (*n* = 9),[3,11,16,19,36,38–40,41] Germany (*n* = 7),[12,17,18,22,30,32,37] the United States of America (*n* = 3),[28,31,33] Switzerland (*n* = 3),[5,29,35] South Korea (*n* = 3)[13,21,34] and France (*n* = 1).[14] The robotic systems used for pedicle screw placement included SpineAssist (*n* = 10),[5,12,18,22,28,29,30,32,35] Renaissance (*n* = 7),[3,13,17,21,33,34,37] TiR7obot (*n* = 7),[16,19,36,38–40,41] ROSA (*n* = 1),[14] and Orthbot (*n* = 1).[11] Five studies were found to have a low risk for randomization sequence generation[13,16,21,34,36] and four did not provide this information.[11,22,30,39] Seven studies showed a low risk in concealing allocation,[11,13,16,21,34,36,39] with two not providing this information.[23,32] Due to the nature of intervention, it was not possible to blind participants and therapists in any study. In seven of the included studies, outcome assessers were not blinded to the group allocation.[11,13,16,21,22,36,39] Only one study showed a high risk in incomplete outcome data and selective outcome reporting.[30] A summary of the risk of bias assessment of the RCTs is displayed in Supplementary Figs. 1 and 2. The risks of bias of the included cohort studies are displayed in Supplementary Table 5. The characteristics of the included studies are shown in Supplementary Table 6.

### Primary outcomes

**Perfect pedicle screw insertion (grades A).** 23 studies (1949 participants, 9319 pedicle screws) compared the differences in perfect pedicle screw insertion (Figure 2A).[3,5,8,11–14,16,17–19,21,22,28,29,30,32,34–36,38–40,41] The pooled estimates (Figure 2B) showed that Renaissance (OR, 2.86; [95% CI, 1.79 to 4.57]) and TiRobot (OR, 3.10; [95% CI, 2.19 to 4.40]) were associated with higher rates of perfect pedicle screw insertion than conventional freehand technique in the consistency model. Moreover, Renaissance (OR, 2.38; [95% CI, 1.37 to 4.13]) and TiRobot (OR, 2.58; [95% CI, 1.64 to 4.07]) were associated with higher rates of perfect pedicle screw insertion than SpineAssist in the consistency model. However, ROSA (OR, 2.10; [95% CI, 0.45 to 9.77]), SpineAssist (OR, 1.20; [95% CI, 0.90 to 1.61]) and

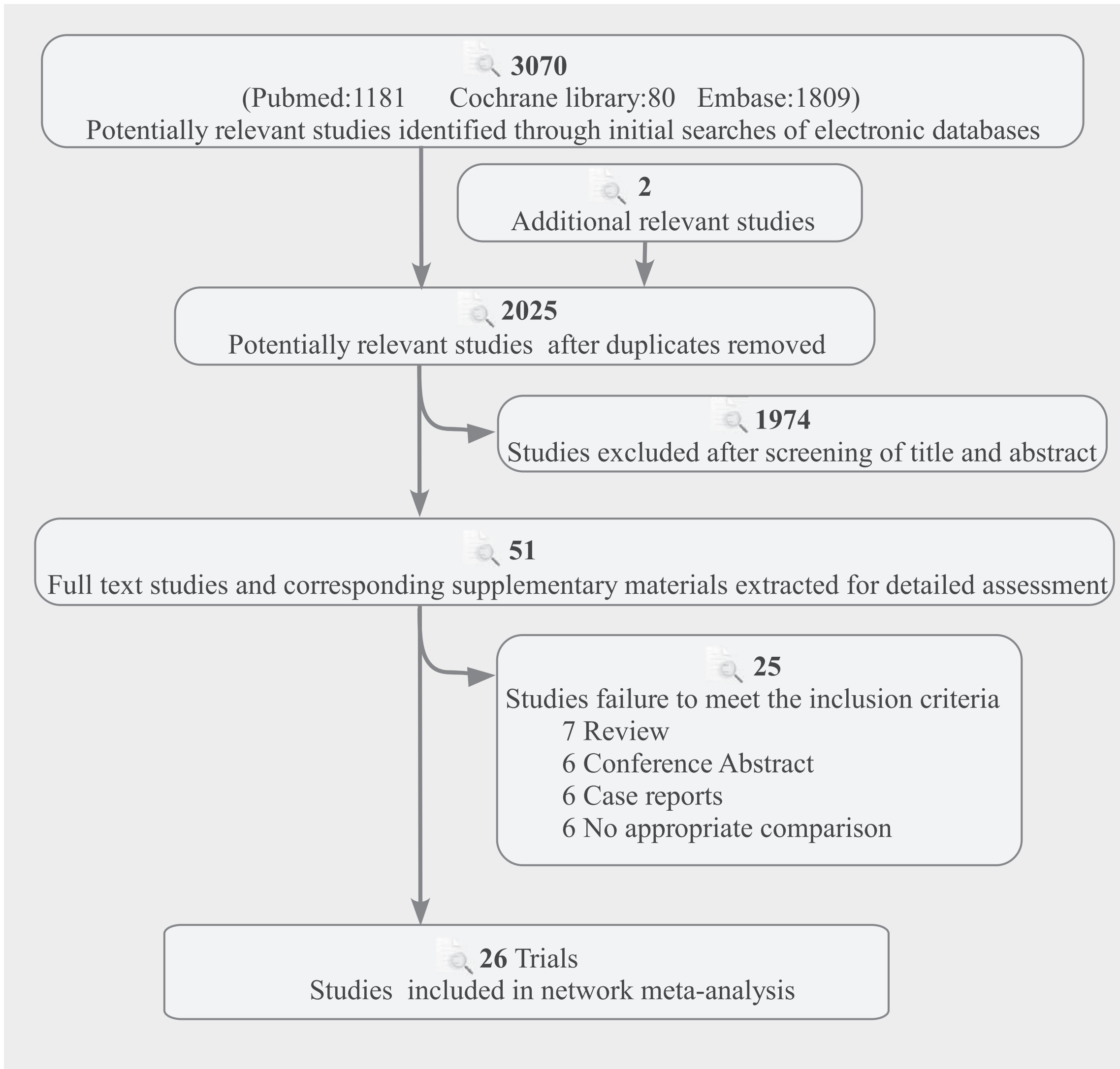
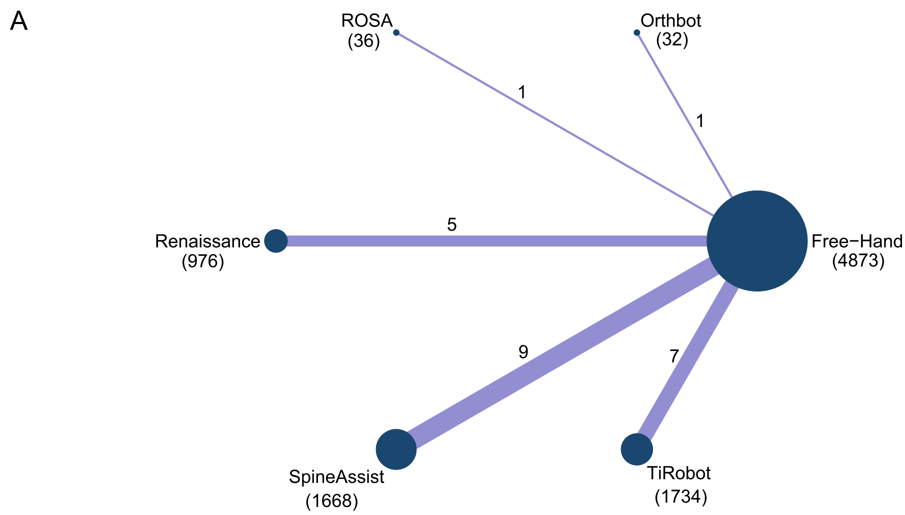



**Figure 1.** Literature search and screening process.

Orthobot (OR, 2.73; [95% CI, 0.61 to 12.27]) were not associated with higher rates of perfect pedicle screw insertion. Figure 3 shows the direct (Supplementary Figs. 3–7) and indirect results of comparing different interventions. The direct results were consistent with the corresponding indirect results regarding significance and tendency. TiRobot (SUCRA: 77.4) was associated with higher rates of perfect pedicle screw insertion, followed by Renaissance (SUCRA: 71.5), Orthbot (SUCRA: 64.7), ROSA (SUCRA: 53.3), SpineAssist (SUCRA: 25.6) and Free-hand (SUCRA: 7.4) (Figure 4A). Subgroup analysis showed that the robot system type affected perfect pedicle screw insertion results (Supplementary Figure 8).

**Clinically acceptable pedicle screw insertion (grades A +B).** 23 studies (1949 participants, 9319 pedicle screws) compared the differences in clinically acceptable pedicle screw insertion rates (Figure 2A).[3,5,8,11–14,16,17–19,21,22,28,29,30,32,34–36,38–40] As shown in Figure 2B, Renaissance (OR, 2.82; [95% CI, 1.51 to 5.25]) and TiRobot (OR, 4.58; [95% CI, 2.65 to 7.89]) were associated with higher rates of clinically acceptable pedicle screw insertion than conventional freehand technique in the consistency model. Moreover, Renaissance (OR, 2.55; [95% CI, 1.25 to 5.19]) and TiRobot (OR, 4.14; [95% CI, 2.17 to 7.89]) were associated with higher rates of clinically acceptable pedicle screw insertion than SpineAssist in the consistency model. However, ROSA (OR,




B

Perfect pedicle screw insertion | Comparison | Clinically acceptable pedicle screw

| | | | | | |
|---|---|---|---|---|---|
| **TiRobot** | **0.24 (0.13,0.46)** | 0.67 (0.06,7.06) | 0.62 (0.27,1.40) | 0.43 (0.02,11.91) | **0.22 (0.13,0.38)** |
| **2.58 (1.64,4.07)** | **SpineAssist** | 2.75 (0.27,28.14) | **2.55 (1.25,5.19)** | 1.78 (0.07,48.00) | 0.90 (0.64,1.28) |
| 1.48 (0.31,7.18) | 0.57 (0.12,2.75) | **ROSA** | 0.93 (0.09,10.01) | 0.65 (0.01,35.39) | 0.33 (0.03,3.27) |
| 1.09 (0.61,1.95) | **0.42 (0.24,0.73)** | 0.73 (0.15,3.67) | **Renaissance** | 0.70 (0.02,19.61) | **0.35 (0.19,0.66)** |
| 1.14 (0.24,5.33) | 0.44 (0.10,2.04) | 0.77 (0.09,6.61) | 1.05 (0.22,5.06) | **Orthbot** | 0.51 (0.02,13.43) |
| **3.10 (2.19,4.40)** | 1.20 (0.90,1.61) | 2.10 (0.45,9.77) | **2.86 (1.79,4.57)** | 2.73 (0.61,12.27) | **Free-Hand** |

**Figure 2.** Network plots of comparisons for perfect pedicle screw insertion and clinically acceptable pedicle (A) based network meta-analyses. Each circular node represents a type of treatment. The circle size is proportional to the total number of pedicle screws. The width of lines is proportional to the number of studies performing head-to-head comparisons in the same study. Perfect pedicle screw insertion and clinically acceptable pedicle profiles (B) based network meta-analyses in the consistency model. Each cell profile contains the pooled Odds ratio (OR) and 95% confidence interval (CI); significant results are in bold.

3.04; [95% CI, 0.31 to 30.31]), SpineAssist (OR, 1.11; [95% CI, 0.78 to 1.56]) and Orthobot (OR, 1.97; [95% CI, 0.07 to 52.11]) were not associated with higher rates of clinically acceptable pedicle screw insertion than conventional freehand technique in the consistency model. Figure 3 shows the direct (Supplementary Figs. 9−13) and indirect results of comparing different interventions. The direct results were consistent with the corresponding indirect results in significance and tendency. TiRobot (SUCRA: 83.9) was associated with a high clinically acceptable pedicle screw insertion rate, followed by Renaissance (SUCRA: 63.6), ROSA (SUCRA: 61.7), Orthbot (SUCRA: 48.4), SpineAssist (SUCRA: 26.1) and Free-hand (SUCRA: 16.2) (Figure 4A). The cluster analysis results based on perfect pedicle screw insertion and clinically acceptable pedicle screw insertion are shown in Figure 4B. Subgroup analysis showed that the robot systems type, images, and operation affect clinically acceptable pedicle screw insertion (Supplementary Figure 14).

**Proximal facet joint violation.** Seven studies (799 participants, 2574 pedicle screws) compared the differences in proximal facet joint violation.[3,16,21,34,37,38,40] The pooled analysis showed that robot-assisted techniques

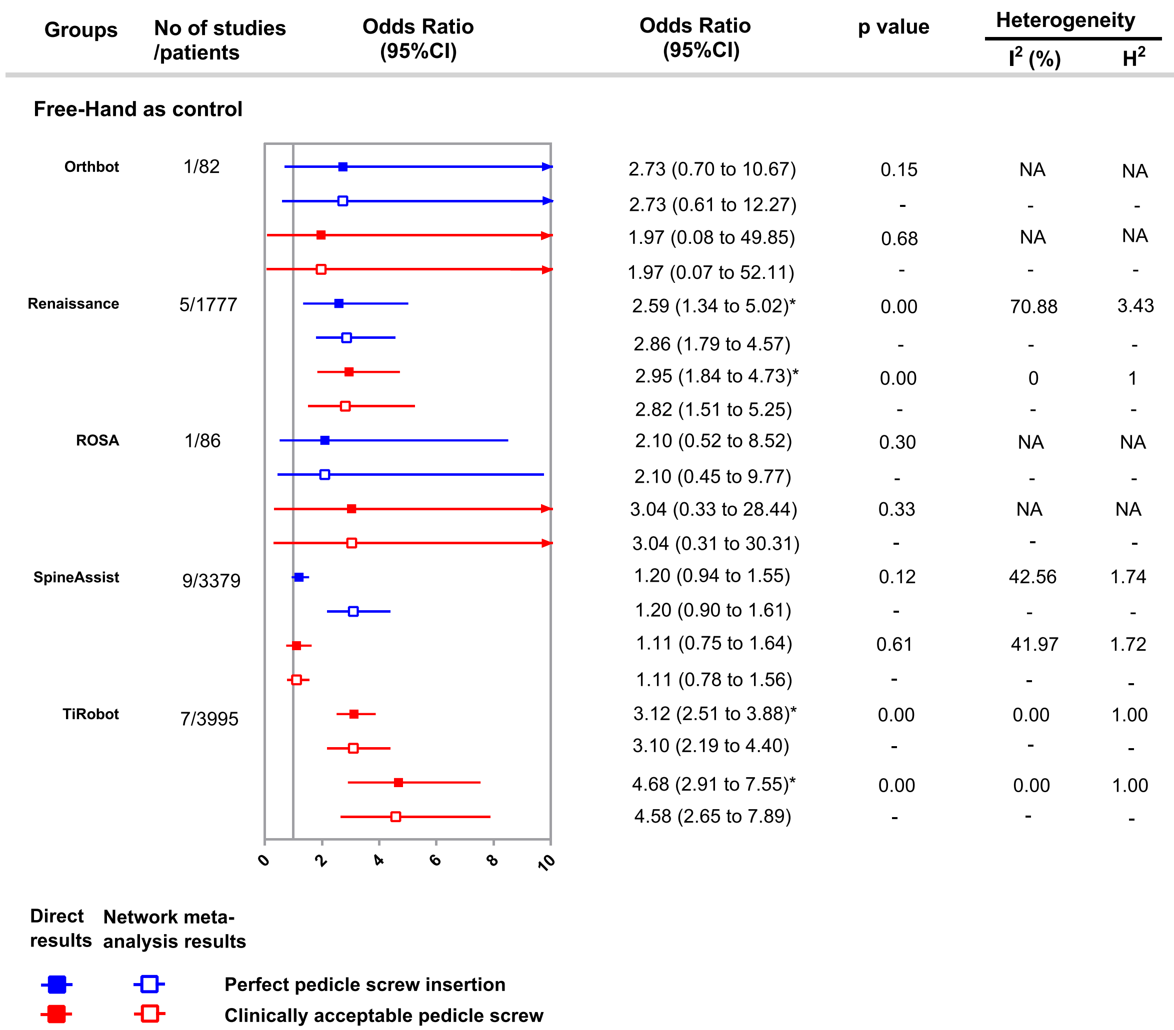



**Figure 3.** Forest plots depicting the direct and indirect results of perfect pedicle screw insertion and clinically acceptable pedicle profiles.
*Values in brackets are 95% confidence interval (CI).

were associated with low proximal facet joint violation rates (OR, 0.18; [95% CI, 0.10 to 0.32]; Figure 5A). Egger's test ($P = 0.3974$) revealed no significant publication bias. Less than 10% heterogeneity was found in studies reporting proximal facet joint violation (Figure 5A). A pairwise meta-analysis was performed, given the small number of studies and the low heterogeneity.

**Overall complications.** 11 studies (932 patients) compared the differences in overall complications.[3,8,12,17,19,21,22,32,33,35] The pooled analysis showed that robot-assisted techniques were associated with low overall complications rates (OR, 0.38; [95% CI, 0.23 to 0.63]; Figure 5B). Egger's test ($P$ = 0.1316) revealed no significant publication bias in overall complications. Less than 30% heterogeneity was found in studies reporting overall complications (Figure 5B). A pairwise meta-analysis was performed, given the small number of studies and the low heterogeneity. Then we conducted a sensitivity analysis including only studies of high quality. Sensitivity analysis showed that the results were stable (Supplementary Figure 15). Four studies (568 participants, 2544 pedicle screws) compared the differences in screw misplacement rate.[16,18,32,35] The subgroup analysis (Supplementary Figure 16) showed no difference in screw misplacement rate between SpineAssist and the conventional freehand technique (OR, 0.63; [95% CI, 0.30 to 1.32]). Moreover, TiRobot (OR, 0.24; [95% CI, 0.12 to 0.45]) was associated with lower rates of screw misplacement rate than the conventional freehand technique.

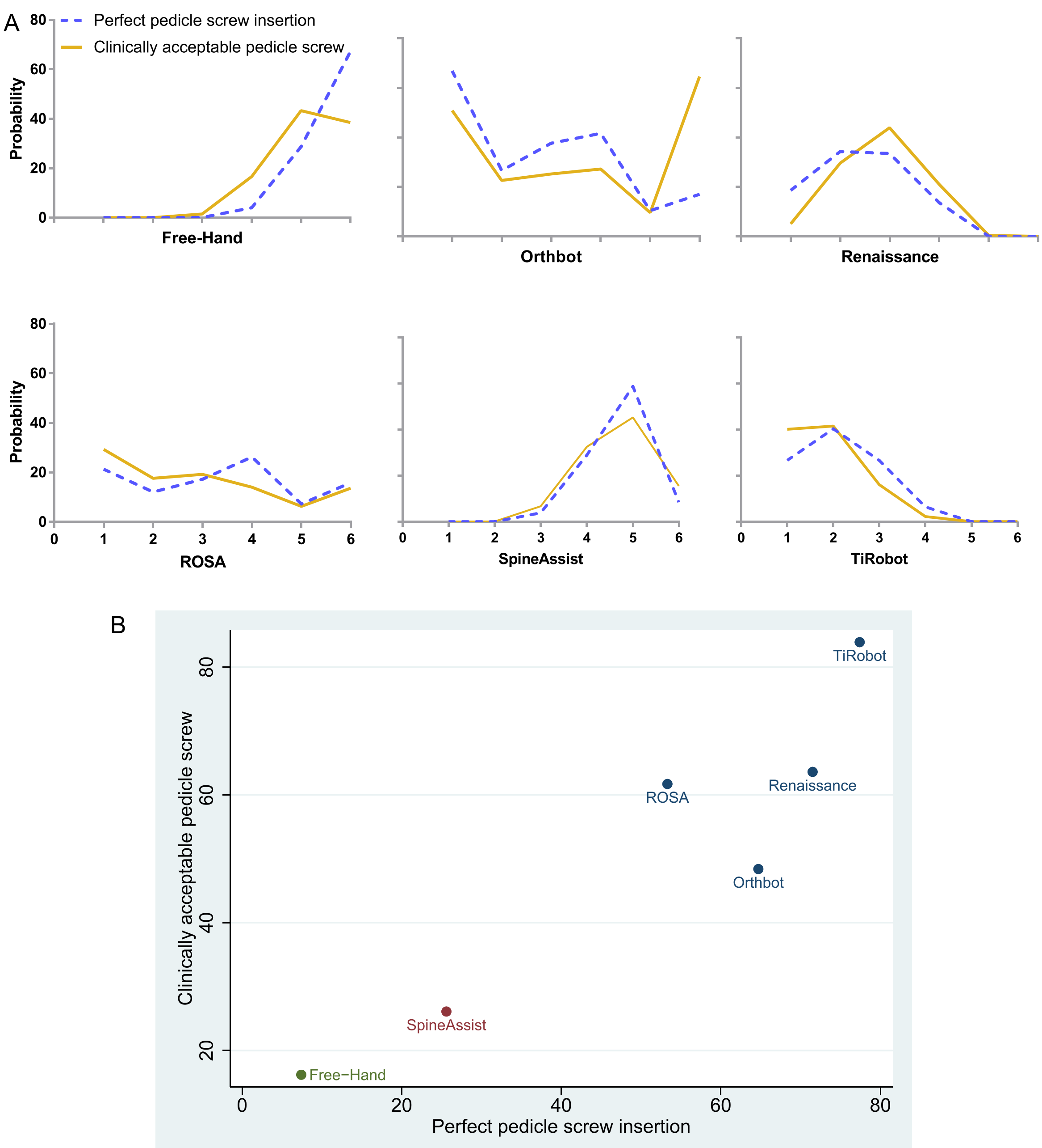



**Figure 4.** Ranking curves (A) indicate the probabilities of perfect pedicle screw insertion and clinically acceptable pedicle. Clustered ranking plot (B) of different interventions for perfect pedicle screw insertion and clinically acceptable pedicle.

## Secondary outcomes

**Radiation exposure time.** 11 studies (1136 participants) compared the differences in radiation exposure time.[3,11,14,16,28,29,30,34,35,38,40] The pooled analysis showed no difference in radiation exposure time between robotic-assisted techniques and the conventional freehand technique (MD, 2.45; [95% CI, -10.61 to 15.51]; Figure 6A). Egger's test ($P$ = 0.4917) revealed no significant publication bias. Significant heterogeneity (>90%) was found in studies reporting on radiation exposure time (Figure 6A). The contour-enhanced funnel plot (Supplementary Figure 17) showed significant publication bias. Subgroup analysis showed that ROSA (MD, 49.80; [95% CI, 44.55 to 55.05]) and TiRobot (MD, 10.96; [95% CI, 4.27 to 17.65]) robot-assisted techniques were associated with more radiation exposure

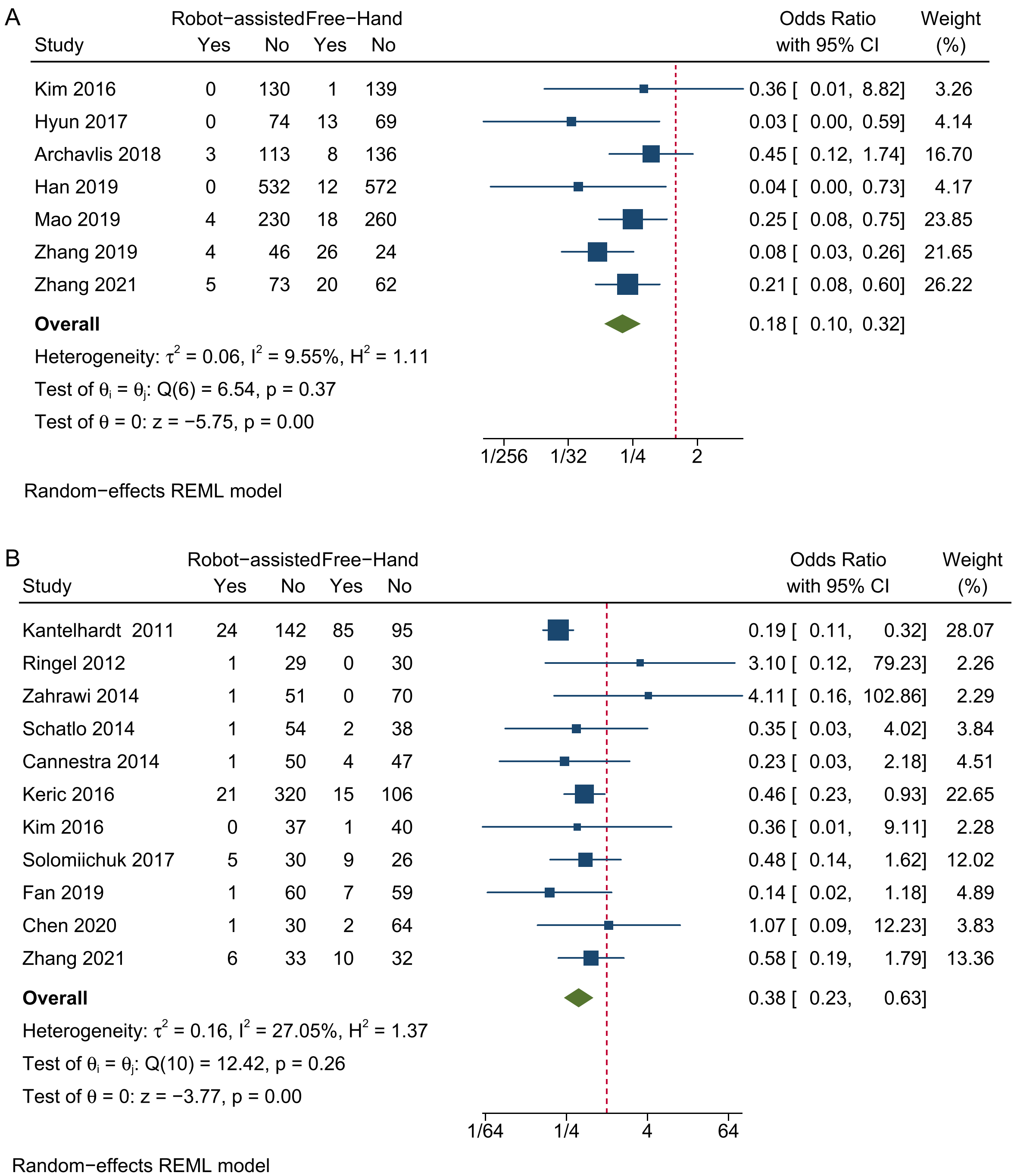



**Figure 5.** Pooled analysis of proximal facet joint violation (A) and overall complications (B) during the comparison between the robot-assisted technique versus the conventional freehand technique.

time than the conventional freehand technique (Supplementary Figure 18).

**Radiation dosage.** Nine studies (1028 participants) compared the differences in radiation dose.[16,28,29,30,34,35,44–46] The pooled analysis showed that robotic-assisted techniques were associated with lower radiation doses than the conventional freehand technique (MD, -14.38; [95% CI, -25.62 to -3.13]; Figure 6B). Egger's test ($P$ = 0.0002) revealed significant publication bias. Significant heterogeneity

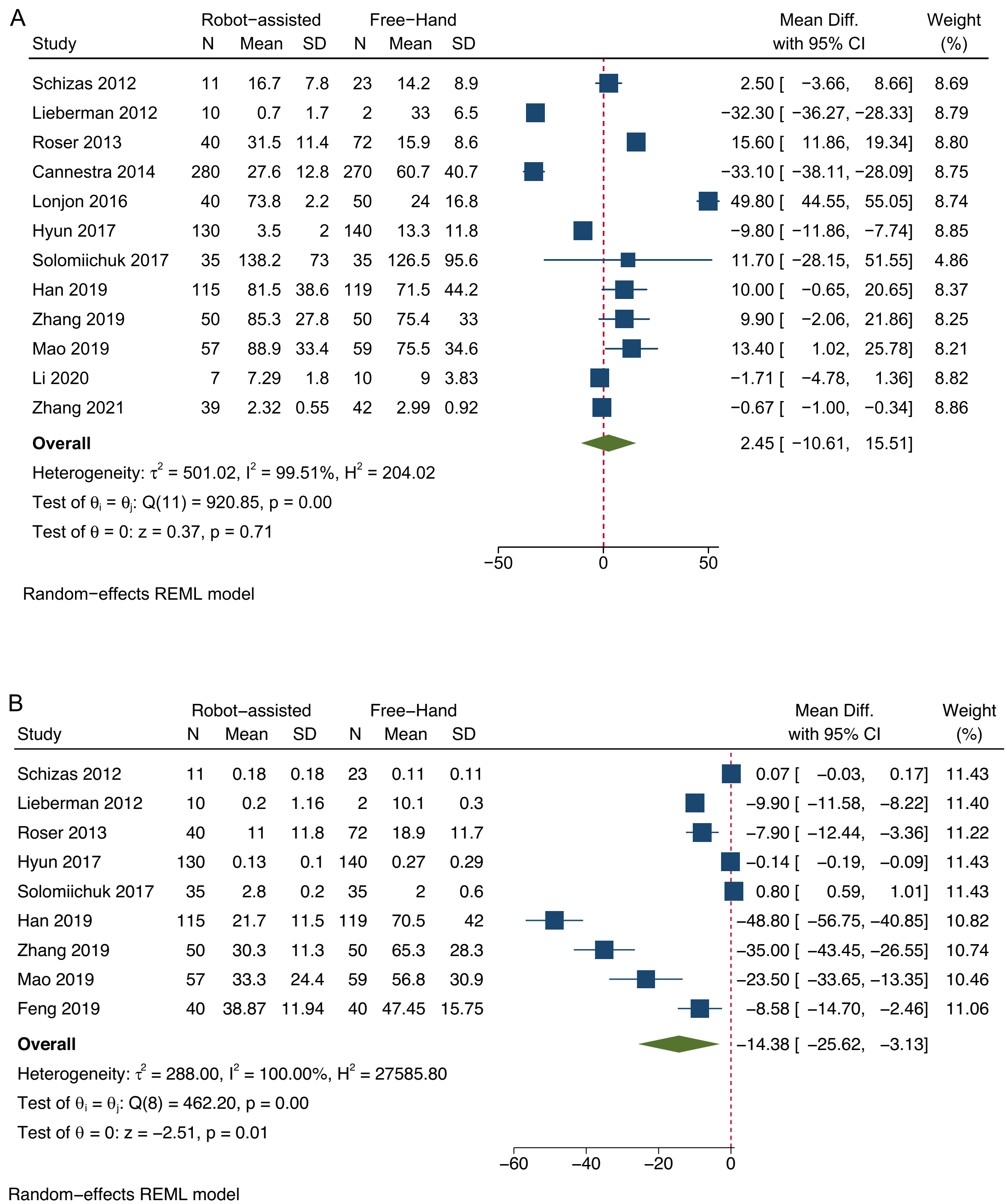



**Figure 6.** Pooled analysis of radiation exposure time (A) and radiation dose (B) during the comparison between the robot-assisted technique versus the conventional freehand technique.

(> 90%) was found in studies reporting radiation doses (Figure 6B). The contour-enhanced funnel plot (Supplementary Figure 19) showed significant publication bias. Subgroup analysis showed that Renaissance (MD, -0.14; [95% CI, -0.19 to -0.09]) and TiRobot (MD, -28.89; [95% CI, -45.86 to -11.91]) robot-assisted techniques were associated with higher radiation doses than the conventional freehand technique (Supplementary Figure 20).

**Operative time.** 17 studies (1429 participants) compared the differences in operative time.[3,8,11,12,14,16,17,19,21,28,32,34–36,38–40] The pooled analysis showed that robot-assisted techniques were associated with longer operative time than the conventional freehand technique (MD, 13.77; [95% CI, 0.14 to 27.39]; Supplementary Figure 21). Egger's test (*P* = 0.0002) revealed significant publication bias in operative time. Significant heterogeneity was found in studies reporting operative time (Supplementary Figure 21). The contour-enhanced funnel plot (Supplementary Figure 22) showed significant publication bias. The subgroup analysis showed that the ROSA (MD, 74.00; [95% CI, 51.81 to 96.19]) robot-assisted technique was associated with longer operative time than the conventional freehand technique (Supplementary Figure 23). Two studies (92 participants, 661 pedicle screws) compared the differences in per pedicle screw time.[28,39] The pooled estimates (Supplementary Figure 24) showed no difference in pedicle screw time between robotic-assisted techniques and the conventional freehand technique (MD, -1.20; [95% CI, -3.17 to 0.77]). However, these results should be interpreted with caution, given that few studies have reported pedicle screw time.

## Discussion

Pedicle screw fixation is widely used to treat different spinal diseases such as unstable spinal fractures, degenerative spinal diseases, spinal deformities and tumors.[34,42] Its most common complication is screw dislocation,[43] reported with an incidence of 3–55%.[44] Indeed, the accuracy of pedicle screw placement is critical for the success of the surgery.[1] In recent years, robot-assisted technology has developed rapidly and is increasingly being used in spinal surgery to improve the accuracy of screw placement.[45] Although some meta-analyses have analysed the accuracy of robotic-assisted pedicle screw fixation, no emphasis was placed on the different robotic systems used, resulting in inconsistent results and significant heterogeneity within studies.[2,8,10,45] Accordingly, we conducted this network meta-analysis to compare the accuracy of different robotic systems for pedicle screw placement. A total of 26 trials, including 2046 participants, were included in this study. We found that only the Renaissance and TiRobot systems had higher accuracy rates of pedicle screw placement than the traditional freehand technique. Moreover, robot-assisted techniques were associated with low rates of proximal facet joint violation and overall complications.

Accurate pedicle screw placement is a challenge faced by many spine surgeons. With the rapid development of robotics, robotic-assisted technology has been introduced into spine surgery, yielding promising results.[46] Its minimal invasiveness and precision during screw placement are key factors that appeal to spine surgeons and patients.[32] The current study showed that Renaissance and TiRobot systems had higher accuracy rates (Grades A or Grades A+B) for pedicle screws placement. In contrast, the other systems exhibited similar accuracy rates to the traditional freehand technique. Gao et al. performed a meta-analysis based on 6 RCTs and a subgroup analysis based on whether the study was randomized or not.[2] Ultimately, they found no significant difference in pedicle screw placement accuracy between the robotic-assisted and the traditional freehand technique.[10] In contrast, an increasing body of evidence suggests that robot-assisted techniques exhibit higher accuracy than the traditional freehand technique.[8,10,45] Unfortunately, no emphasis was placed on the robotic system used, resulting in highly heterogeneous results and unreliable conclusions. Importantly, the present study evaluated whether robotic systems were more effective for pedicle screws and identified differences between systems. In addition, an educated guess is that screw dislocation rates are higher in patients with spinal metastases and infectious disease. In a subgroup analysis for metastatic spinal disease, robotic assistance only improved the rate of perfect pedicle screw insertion by 40% (Supplementary Figure 25). And the clinically acceptable pedicle screw insertion rate was not significantly different from freehand techniques (Supplementary Figure 26). It is possible that metastatic spinal disease is associated with osteolysis, which could potentially affect the automatic identification accuracy of surgical assist systems based on cortical bone contours.[35]

It is well-established that safety and efficacy are equally important for any emerging technology, providing surgeons with a comprehensive understanding of its strengths and limitations.[47] In the present study, robotic-assisted techniques were associated with low proximal facet joint violation rates. Egger's test was used to test for publication bias. A pairwise meta-analysis was performed, given the small number of studies and the low heterogeneity. The findings of this study were consistent with the literature.[10,25,45] In addition, we found that robotic-assisted techniques were associated with low overall complications rates, consistent with the previous studies.[10,16,21,34] This discrepancy can be attributed to a certain extent to the fact that traditional freehand techniques depend primarily on the skill and experience of the surgeon. Furthermore, robotic-assisted techniques enable surgeons to select the optimal trajectory for pedicle screws, facilitating facet joint avoidance.[45] Results of our comprehensive evaluation suggest that this robotic-assisted approach is safe.

Current evidence suggests that surgeons are often at risk of intraoperative radiation exposure during spine surgery, which can be deleterious.[48] Our study found no difference in radiation exposure time between robot-assisted and conventional freehand techniques. Moreover, the subgroup analysis showed that ROSA and TiRobot robot-assisted techniques were associated with longer radiation exposure than the conventional freehand technique. Interestingly, these findings were not consistent with the literature.[10,45] Indeed, it is highly conceivable that this discrepancy may be attributed to the more significant number of updated trials included in this meta-analysis. Moreover, the robotic system relied on intraoperative X-ray 3D scanning images for planning, while the freehand group did not require 3D scanning before pedicle screw placement.[38] Nonetheless, the radiation exposure dose in the robot-assisted group was lower than in the freehand group, consistent with the literature.[2,10,45] One potential reason for this inconsistency between radiation exposure time and radiation dose is that doctors and other staff often keep a safe distance to avoid radiation during intraoperative 3D scanning. Our study showed that robot-assisted techniques were associated with longer operative time than the conventional freehand technique, consistent with the previous studies.[10,14,40] This finding may be due to the learning curve and the need for navigational imaging during the intraoperative preparation phase.[8,30]

Several robotic systems like CIRQ® (Brainlab Germany),[49] Excelsius GPS® (Globus Medical),[50] Mazor X (Mazor Robotics Ltd., Caesarea, Israel),[51] and Curexo® (Curvis-spine, South Korea)[52] were not included in our study due to no suitable controlled studies. It has been reported that the lightweight and table-mounted aspects of the new CIRQ® arm are intended to be more ergonomic and less disruptive to operative workflow relative to larger robotic units. In an initial trial of CIRQ® in a small number of patients, 97.1% of screws did not require intraoperative revision.[53] The Excelsius GPS system has the functions of intraoperative real-time imaging and automatic compensation of patient motion.[54] Vardiman et al. reported that only 1.5% (9/600) were repositioned intraoperatively.[54] Moreover, Mazor X® allows the robot to perform a volumetric assessment of the working environment to self-detect its position and provide intraoperative collision avoidance.[9] Khan et al. reported 98.7% accuracy for direct insertion into the pedicle and *a* < 2 mm breach of a single screw.[55] Finally, Curexo® is a robot-assisted spine surgery system that uses a C-arm-based navigation system.[52] Kim et al. reported that accuracy rates for pedicle screws placement were less accurate than in other studies on human patients (Grades A+B: 80.4%),[52] which may be attributed to the fact that the robot is still at a developmental stage.

To the best of our knowledge, this is the first network meta-analysis to compare the accuracy rates of different robotic systems for pedicle screw placement. Importantly, we innovatively compared the indirect results (network meta-analysis results) with the pairwise direct results (meta-analysis results) to explore the source of heterogeneity. However, there were some inevitable limitations in our study. First, not all of the included studies were RCTs; nonetheless, the quality of the cohort trials was assessed as moderate. Some robotic systems were evaluated with only one trial,[11,14] resulting in less robust conclusions. Besides, due to the significant cost and time required to adopt these systems, it is difficult to directly compare the screw placement accuracy among these systems. Accordingly, network meta-analysis can be a practical analytical approach in such circumstances.[56] Furthermore, for secondary outcomes, we should interpret them with caution due to the high risk of publication bias. It is probably due to that studies that examined the initial experience and learning curves were included in the meta-analysis, which may have contributed to unreliable results. In addition, some robotic systems were evaluated with only one trial resulting in less robust conclusions. Moreover, the expertise of surgeons may be a potential source of heterogeneity. Accordingly, large-scale RCTs using robot-assisted techniques are needed to improve our knowledge of this new technology.

This network meta-analysis substantiate the accuracy of Renaissance and TiRobot systems for accurate pedicle screw placement. In addition, robotic-assisted techniques were associated with less proximal facet joint violation and radiation exposure than freehand techniques but featured longer operative times. Our findings demonstrate that robots have huge prospects for clinical application to assist doctors place pedicle screws safely and effectively.

## Contributors

Dr Yan, Qian, and Wei have accessed and verified the data in this study, and they take responsibility for data integrity and accuracy of analysis. Wei, Gao and Heng contributed equally to this manuscript. Yan, Qian, Wei, Zhou, Gao and Heng conceived and designed the work. Wei, Gao, Heng, Yuan, Zhu, Yang, Du, Zhou, Qian and Yan acquired and analyzed data, interpreted results. Wei, Gao and Heng wrote the manuscript. All authors contributed to critical revision of the manuscript for important intellectual content. Wei, Gao and Zhou performed statistical analysis. Yan, Qian, Zhou, Wei, Gao and Heng contributed to administrative, technical, or material support. Yan, Qian, Zhou, Wei, Gao supervised. All authors had full access to all the data in the study, and accept responsibility to submit for publication.

## Data sharing statement

This meta-analysis of secondary analysis of raw data from published original articles. All the data used for the study are included in the manuscript and supplementary material.

## Declaration of interests

We declare no competing interests.

## Acknowledgments

This study was supported by the National Natural Science Foundation of China, Tangdu Hospital Seed Talent Program and Natural Science Basic Research Plan in Shaanxi Province of China. We thank Tangdu Hospital, Fourth Military Medical University for supporting our work and Home for Researchers (www.home-for-researchers.com) for a language polishing service.

## Funding

This work was supported by grants from the National Natural Science Foundation of China (No. 81871818), Tangdu Hospital Seed Talent Program (Fei-Long Wei) and Natural Science Basic Research Plan in Shaanxi Province of China (No.2019JM-265).

## Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.eclinm.2022.101421.

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