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Accuracy of Pedicle Screw Placement Methods in Pediatrics and Adolescents Spinal Surgery: A Systematic Review and Meta-Analysis

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Abstract

Study Design: Systematic review and meta-analysis.

Objective: Various methods of pedicle screw (PS) placement in spinal fusion surgery existed, which can be grouped into conventional freehand (FH), modified freehand (MF), and image-guided methods (including fluoroscopy-based navigation (FL), computed tomography-based navigation (CT-nav), robot-assisted (RA), and ultrasound-guided (UG)). However, the literature showed mixed findings regarding their accuracy and complications. This review aimed to discover which method of PS placement has the highest accuracy and lowest complication rate in pediatric and adolescent spinal fusion surgery.

Methods: A comprehensive search in MEDLINE (PubMed), EMBASE (OVID), CENTRAL, and Web of Science was conducted until May 2020 by 2 independent reviewers, followed by bias assessment with ROB 2 and ROBINS-I tools and quantification with meta-analysis. Overall evidence quality was determined with GRADE tool.

Results: Four RCTs and 2 quasi-RCTs/CCTs comprising 3,830 PS placed in 291 patients (4-22 years old) were analyzed. The lowest accuracy was found in FH (78.35%) while the highest accuracy was found in MF (95.86%). MF was more accurate than FH (OR 3.34 (95% CI, 2.33-4.79), $P < .00001$, $I^2 = 0\%$). Three-dimensional printed drill template (as part of MF) was more accurate than FH (OR 3.10 (95% CI, 1.98-4.86), $P < .00001$, $I^2 = 14\%$). Overall, complications occurred in 5.84% of the patients with 0.34% revision rate. Complication events in MF was lower compared to FH (OR 0.47 (95% CI, 0.10-2.15), $P = .33$, $I^2 = 0\%$).

Conclusions: Meta-analysis shows that MF is more accurate than FH in pediatric and adolescent requiring PS placement for spinal fusion surgery.

Keywords

pedicle screws, pediatrics, adolescents, spinal surgery, systematic review, meta-analysis

Introduction

Surgical techniques and instrumentation for treating various spinal conditions have advanced significantly since 1970, when Roy-Camille pioneered using pedicle screw (PS) in spinal fusion surgery.[1] Despite the high success rate and extensive use, PS utilization in pediatrics and adolescents may lead to unwanted complications resulting from PS misplacement.[2] Pulmonary effusion, leakage of cerebrospinal fluid, neurologic impairment, pedicle fracture, infection, and vascular injuries have been reported as the complications related to PS placement in pediatrics.[3] Moreover, 25% of children who underwent PS placement had asymptomatic misplaced screws adjacent to major blood vessels or viscera.[4] PS misplacement was also

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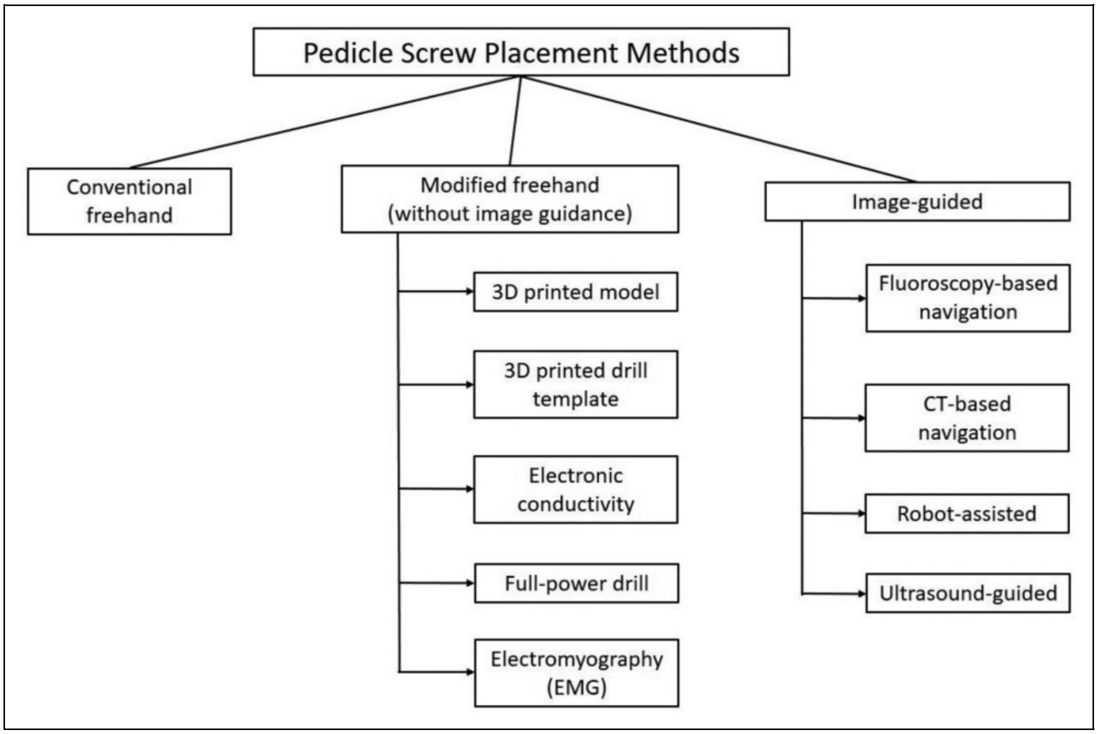

Figure 1. Various methods of pedicle screw (PS) placement.

found to be higher in pediatrics compared to adults, leading to double the rate of revision.[5] This issue was even more challenging in children presenting with complex spinal deformity.[6]

Various procedures have been developed to improve the accuracy of PS placement. In general, they can be grouped into the conventional freehand, modified freehand, and image-guided (Figure 1). The conventional freehand (FH) relies solely on anatomical landmarks; thus requiring adequate knowledge and experience from the spine surgeon through a higher learning curve.[7] We define modified freehand (MF) when the surgeon utilizes non-imaging technology such as 3-dimensional (3D) printed anatomic models,[8] 3D printed drill template,[9] electronic conductivity,[10] full-power assisted (FPA),[11] or electromyography (EMG)[12] to assist PS placement. Whereas, image-guided techniques utilize either fluoroscopy-based navigation (FL), intraoperative computed tomography/CT-based navigation (CT-nav), robotic-assisted (RA),[13] or ultrasound (UG)[14] to help the surgeon visualize the screw position.

A comprehensive systematic review and meta-analysis which covers all techniques in pediatrics and adolescents have never been conducted. Therefore, this review aims to discover which method of pedicle screw placement has the highest accuracy and lowest complication rate in pediatric and adolescent spinal fusion surgery.

Methods

Although this review is not a Cochrane review, the author followed the principles and guidelines from the Cochrane Handbook for Systematic Reviews of Interventions[15] and PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).[16, 17]

Eligibility Criteria

Our inclusion and exclusion criteria were described in Table 1.

Electronic Search

The authors performed a systematic electronic literature search in the main databases:

- MEDLINE: 1966 to present (13th May 2020)
- EMBASE: 1980 to present (13th May 2020)
- The Cochrane Central Register of Controlled Trials (CENTRAL): from inception to 13th May 2020
- Web of Science: 1900 to present (13th May 2020)

We conducted the search with both free-text and subject headings (MeSH for MEDLINE and Emtree for EMBASE). The keywords and search strategy were developed with a consultation to our institutional medical librarian (see Supplementary information for comprehensive list of keywords and search strategy). We elaborated the details of pedicle screw placement methods by using extensive word variations, truncations (*), and wildcards (?) to maximize our search strategy's sensitivity, i.e. to capture as much as possible the literature that was relevant to our research question. Nevertheless, it is crucial to maintain the balance of sensitivity (comprehensiveness) and specificity (precision). Thus, we also formulated our search strategy per PICO concept

Table 1. Inclusion and Exclusion Criteria of This Review.

Inclusion criteria	Exclusion criteria
• Clinical trials (randomized controlled trial (RCT) and quasi-RCT/controlled clinical trial (CCT)) comparing the accuracy of various PS placement methods • Children and adolescents (up to 25 years old) with any spinal conditions requiring PS insertion • Published and unpublished articles that were written in English and available in full-text • No limitation on publication time	• Patients diagnosed with adolescent idiopathic scoliosis (AIS) who were operated during their adulthood (over 25 years old at the time of surgery) • Summaries, letters to editors, summaries of meetings, expert opinion, review, book chapter, study protocol, technical report • Systematic reviews, meta-analyses • Observational studies • Studies with incomplete or unavailable data • Duplicate publication • Animal and cadaveric experimental studies • Morphometric measurement • Finite element analysis • Only reporting anterior instrumentation • Reporting a different type of screw fixation (non-PS) • Including occipitocervical (craniocervical) fixation or sacroiliac fixation in which the data cannot be separated

(Patient, Intervention, Comparison, Outcome) and combined the keywords using appropriate Boolean operators (“AND”, “OR”, “NOT”) to ensure its preciseness.

- P: children (pediatrics) and adolescents with any spinal diseases needing spinal fusion (arthrodesis) with pedicle screw
- I: conventional freehand, modified freehand (3D printed anatomic models, 3D printed drill template, electronic conductivity, FPA, EMG), fluoroscopy, CT, robot, ultrasound
- C: other method(s) described in the intervention (I)
- O: accuracy (breach/perforation), complications, revision surgery rate

We applied an RCT filter provided by PubMed for MEDLINE and the Scottish Intercollegiate Guidelines Network (SIGN) for EMBASE.[18] Full details of the search strategy were reported in Supplementary information. Reference lists of all the studies included and excluded in this review were checked for additional relevant trials.

Study Selection and Data Collection Process

Obtained references were exported into Endnote X9 (Clarivate, Philadelphia, USA) for initial duplicate removal. Two reviewers (BDV and ARN) independently performed the title and abstract screening with Rayyan software.[19] Potentially eligible or unclear studies were included for full-text reading. The reasons for exclusion of studies after full-text reading were recorded. Any discrepancies were solved by discussion with third investigator (DK). The workflow of our study selection process was presented with the PRISMA flowchart.[16, 17]

Selected studies were extracted with Microsoft Excel (Microsoft Corporation, Redmond, USA). Following data was collected: author, year of publication, study design and settings, demographic of patients, indication of surgery, Cobb’s angle, method/technique, total screws inserted, misplaced screws, accurate screws, postoperative complications and revision surgery. We planned to obtain missing data by contacting the trial authors.

Qualitative Assessment

For RCT and quasi-RCT, we assessed the study quality with the Cochrane Risk of Bias (ROB) tool 2.[20] As for CCT, we used the Risk Of Bias In Non-randomized Studies-of Interventions (ROBINS-I) tool.[21]

Quantitative Assessment (Meta-Analysis)

Statistical analysis was performed using RevMan 5.3 (The Nordic Cochrane Centre, Copenhagen, Denmark). We calculated odds ratios (ORs) with 95% confidence interval (CI) for dichotomous data. Heterogeneity (inconsistency) was analysed with Chi^2 (χ^2) and I^2 test. A low P-value ($P < .1$) of χ^2 test and an I^2 >50% indicate a substantial heterogeneity.[22] Unless a substantial heterogeneity was suspected, we used the fixed effects model. Subgroup analysis was performed based on the type of study designs and interventions. To increase the robustness of meta-analysis results, we excluded the trials that were classified as having a high risk of bias from the meta-analysis. When a minimum of 10 trials was included in the meta-analysis, we would conduct the funnel-plot test to assess reporting bias.

Summary of Findings and Level of Evidence

We presented our findings in a “summary of findings” table using GRADE (Grading of Recommendations Assessment, Development and Evaluation) tool to assess the certainty (quality) of the evidence body for a given outcome.[23] The assessment was performed using GRADEpro software (GRADEpro GDT, McMaster University & Evidence Prime, Inc.).

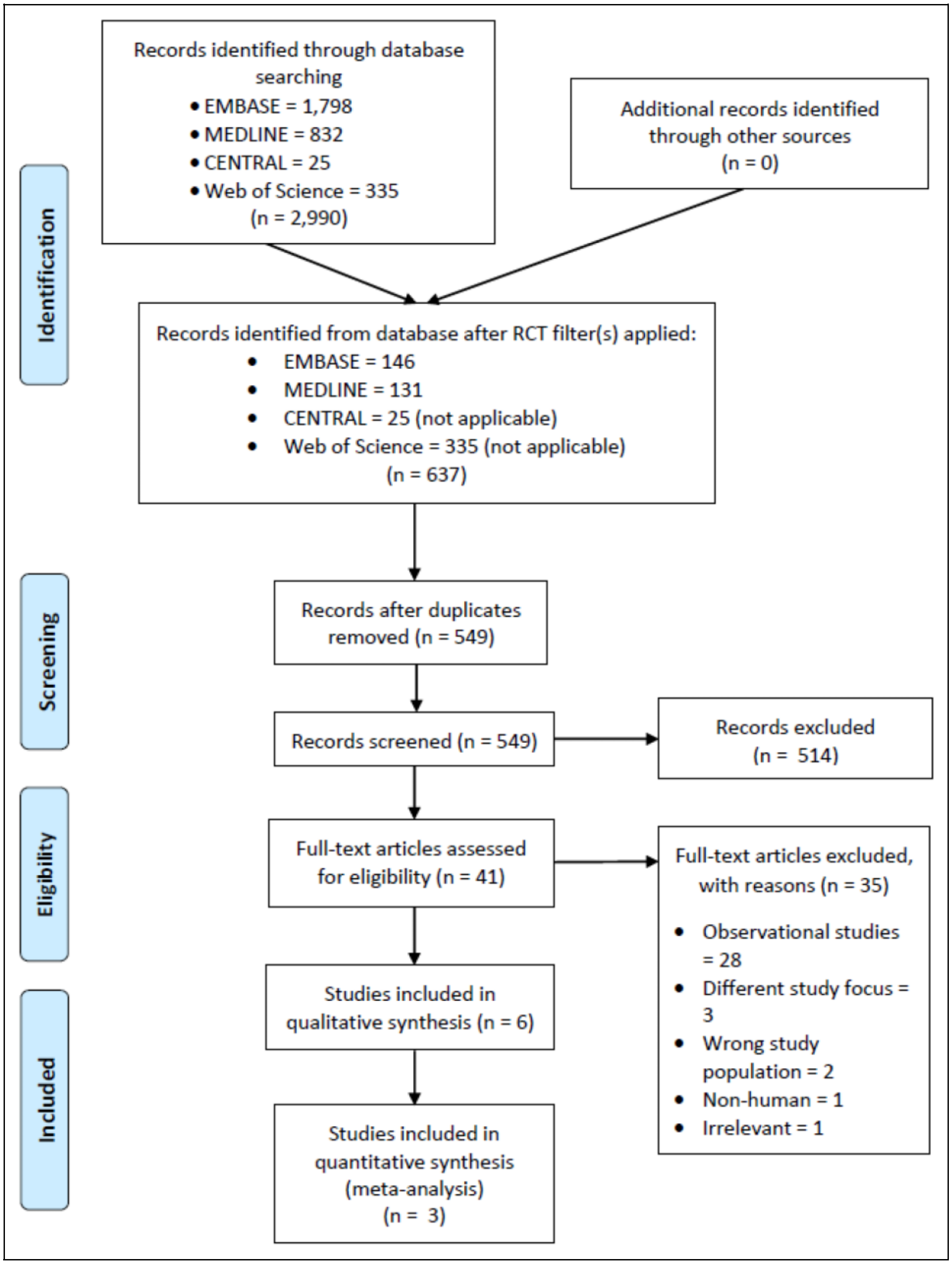

Figure 2. PRISMA flow diagram of this review.

Results

Study Selection

The summary of our workflow was shown in Figure 2.

Study Characteristics

A total of 6 trials (4 RCTs and 2 quasi-RCT/CCT) were included in this review, consisting of 3,830 pedicle screws placed in 291 pediatrics and adolescents aged 4-22 years from 2004 to 2018. From the 5 trials that reported the male/female distribution, 69% were female (151/219), while 31% were male (68/219).[9-11,24,25] Characteristics of the included trials were described in Table 2.

Qualitative Assessment

We appraised the quality of each trial with ROB 2 (Figure 3) and ROBINS-I (Figure 4) tools. Overall, a shortage of

Table 2. Characteristics of the Included Trials.

				Patients		Indication of surgery			
No	Author	Study design	Settings	Male	Female	Congenital Scoliosis	Adolescent Idiopathic Scoliosis	Infection (post-TB kyphosis)	Cobb's angle (mean)
1	Bai et al., 2013	RCT	China	9	33	0	42	0	E & C = 55.3° ± 7° (range 45-78°)
2	Garg et al., 2019	Quasi-RCT	India, single center	7	13	11	7	2	E = 85.3° and C = 90.4°
3	Luo et al., 2019	CCT	China, June 2016-June 2018, single center	11	21	32	0	0	E = 113° ± 15° and C = 106° ± 14°
4	Su et al., 2012	RCT	China, 2006-2008, single center	7	13	0	20	0	E = 58.1° (range 42°-77°) and C = 58.2° (range 48°-78°)
5	Wu et al., 2011	RCT	China, January 2004-January 2007, single center	x	x	62	0	0	E = 85° and C = 75°
6	Yan et al., 2018	RCT	China, June 2014-June 2015, single center	34	71	0	105	0	E = 63.7° ± 15.8° and C = 67.8° ± 18.7°

RCT: Randomized controlled trial; CCT: Controlled clinical trial; E: Experimental group; C: Control group.
x: This study did not record male/female distribution.

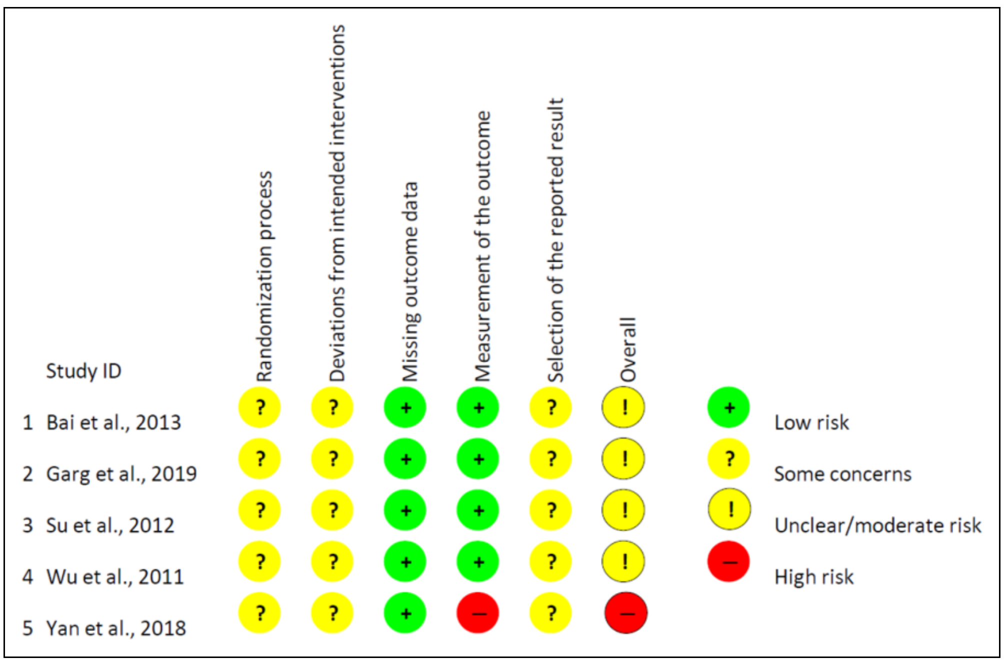

Figure 3. RCT and quasi-RCT assessment of the individual risk of bias with ROB 2.

information in some aspects caused unclear/moderate risk of bias in 5 out of 6 trials, whereas one trial conducted by Yan et al. was judged as having a high risk of bias due to measurement of the outcome.[11] The postoperative CT scan evaluation to assess the accuracy of PS in this trial was 5 mm thick; meanwhile, the ideal CT scan thickness for spine evaluation is 1-2 mm.[26]

The definition of pedicle breach and safe zone (in relation to the risk of injuring vital structures) differed among trials. Two trials classified the pedicle into 3 grades: no breach, up to 4 mm breach, and > 4 mm breach. These trials defined 4 mm as the cut-off point for the safety zone.[8,24] The remaining trials divided the pedicle into 4 grades (grade 0 = no breach, grade 1 = 0-2 mm, grade 2 = 2-4 mm, grade 3 ≥ 4 mm) with 2 mm as

Author, Year	Pre-intervention		At intervention	Post-intervention				Overall Risk of Bias
	Bias due to confounding	Bias in selection of participants into the study	Bias in classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reported result	Low/ Moderate/ Serious/ Critical
Luo, et al., 2019	Low	Low	Low	Moderate	Low	Moderate	Moderate	Moderate

Figure 4. Risk of bias of controlled clinical trial (CCT) assessed by ROBINS-I.

the cut-off for safe zone. We intended to reclassify the breach based on 2 mm increment as recommended by a systematic review[27]; however, we could not actualize it as Yan et al. did not specify the number of misplaced screws in grade 1 (instead only stated the screws as "in" or "out").[11] Therefore, we categorized them into misplaced and accurate screws based on the original definition of breach by the trial authors. Five trials counted any violations/breach as screws misplacement, whether 2 trials[9,11] only counted that above 2 mm as misplaced.

Four interventions were described among trials: the conventional freehand (FH), modified freehand (MF), fluoroscopy-based navigation (FL), and CT-based navigation (CT-nav). Of these, the MF group consisted of 4 methods: electronic conductivity device (ECD), 3D printed drill template, 3D printed anatomic model, and full-power assisted (FPA) technique. No trials using robot-assisted (RA) and ultrasound-guided (UG) method were found. No trial which used electromyography (EMG) alone to assist pedicle screw placement was found. Two trials used intraoperative neuromonitoring system as an adjuvant to monitor the electrophysiology function during surgery; however, they did not specify whether the EMG was used.[11,24] The summary of the outcomes was stated in Table 3.

Quantitative Assessment (Meta-Analysis)

From the 4 trials comparing MF and FH, one trial was excluded from the quantitative assessment (meta-analysis) due to high risk of bias.[11] Finally, we conducted a meta-analysis comparing the accuracy of the PS placement involving 3 trials (OR 3.34 (95% CI, 2.31-4.76), $P < .00001$, $I^2 = 0\%$) (Figure 5). Whereas, the other trials comparing CT-nav versus FH and MF (3D printed anatomic model) versus FL were not included as there were no comparisons.

Postoperative complication rate between MF and FH was quantified, and the meta-analysis (Figure 6) showed that MF caused fewer complications compared to FH (OR 0.47 (95% CI, 0.10-2.15), $P = .33$, $I^2 = 0\%$).

Summary of Findings and Level of Evidence

The summary of the outcomes and level of evidence of this review was shown in Figure 7. Overall, the evidence for PS accuracy was low and the evidence for complication rate was very low.

Discussion

Summary of Main Results

Almost all of the trials used FH as the control group, except Wu et al. who used FL as the control group.[8] Overall, the accuracy in the experimental group was better than the control group in all 6 included studies. The lowest accuracy was 78.35% seen in FH,[9] while the highest accuracy was 95.86% seen in MF using ECD.[10] In the meta-analysis, we included 3 trials with matching head-to-head comparisons (MF versus FH).[9,10,24] Regardless of the various methods within MF, this group had the same key characteristics, i.e. not using image-guided technique yet not merely conventional freehand. The consistency within the groups was demonstrated quantitatively with the statistical test for heterogeneity. The Chi^2 test showed a high P-value (.28) and $I^2 = 0\%$, which means the difference in patient characteristics and variety within MF group caused no issue, i.e. the groups were comparable. One trial used ECD, which assisted the surgeon by utilizing the principle of microarchitecture difference between cancellous and cortical bone captured by electromagnetic sensors.[10] Two trials used rapid prototyping technology in the form of 3D printed drill template.[9,24] The meta-analysis showed increased accuracy of PS when placed with MF (OR 3.34 (95% CI, 2.33-4.79), $P < .00001$, $I^2 = 0\%$).

Agreement and Disagreements With Other Studies or Reviews

Patient characteristics. The present review showed that two-thirds of the patients were female. Zhang et al. also found a female-to-male scoliosis prevalence ratio of 1.54 (95% CI, 1.35-1.74; $P < .001$) in primary and middle school students aged 4-20 years.[28] Being female increased the chance of developing scoliosis by 4.7 times with the peak incidence was found during puberty (13-14 years old).[29] Some researchers have identified genetic roles in scoliosis and curve progression,[30] with female was known to have a 10-fold higher risk of curve progression.[31] Although hormonal disturbance during puberty and mutation in estrogen receptors genes were suspected to be the cause, a recent meta-analysis showed the contrary.[32] Therefore, the exact etiology and pathogenesis of scoliosis are yet to be defined.

Comparisons of various pedicle screw placement methods. Concern about the complication that may arise due to misplaced screws

Table 3. Summary of the Outcomes (Accuracy, Complications and Revision Surgery).

No	Author	Intervention/ method	Total screw placed	Accurate screws	Misplaced screws	Accuracy rate	Odds ratio (95% CI), test for overall effect (*P*-value)	Total patients	Postoperative complications	Treatment	
										Conservative	Revision surgery
1	Bai et al., 2013	MF (Electronic conductivity)	362	347	15	95.86%	3.18 (1.81-5.60), $P < .001$	20	0	0	0
		FH	332	285	47	85.84%		22	0	0	0
2	Garg et al., 2019	MF (3D printed drill guide)	137	125	12	91.24%	2.20 (1.04-4.66), $P = .04$	10	2 (superficial wound infection)	Change of antibiotics	0
		FH	126	104	22	82.54%		10	2 (superficial wound infection)	Change of antibiotics	0
3	Luo et al., 2019	MF (3D printed drill guide)	244	227	17	93.03%	3.69 (2.09-6.50), $P < .00001$	15	1 (presumed neurological injury)	Sodium aescinate (anti-inflammatory agent), mouse nerve growth factor (reduces myelin edema)	0
		FH	291	228	63	78.35%		17	4 (1 nerve compression, 2 CSF leakage, 1 anterior breach but did not violate the aorta)	For CSF leakage: intravenous injection of high amount normal saline, foot elevation For anterior breach near aorta: close monitoring	1 (nerve compression)
4	Su et al., 2012	CT-nav	169	159	10	94.08%	2.50 (1.15-5.44), $P = .02$	10	0	0	0
		FH	169	146	23	86.39%		10	0	0	0
5	Wu et al., 2011	MF (3D printed anatomic model)	383	358	25	93.47%	2.59 (1.55-4.33), $P = .0003$	34	3 incomplete root injuries	Patients recovered after 3-6 months of conservative treatment	0
		FL	294	249	45	84.69%		38	5 (1 hematoma, 2 incomplete root injuries, 2 complete cord injuries)	For incomplete root injuries: recovered after 6 months of conservative treatment For complete cord injuries: no details about recovery.	0
6	Yan et al., 2018	MF (Full-power assisted (FPA) technique)	427	380	47	88.99%	1.14 (0.80-1.64), $P = .47$	35	0	0	0
		FH	896	785	111	87.61%		70	0	0	0

FH: Conventional Freehand; MF: Modified Freehand; CT-nav: CT-based navigation; FL: Fluoroscopy-based navigation.

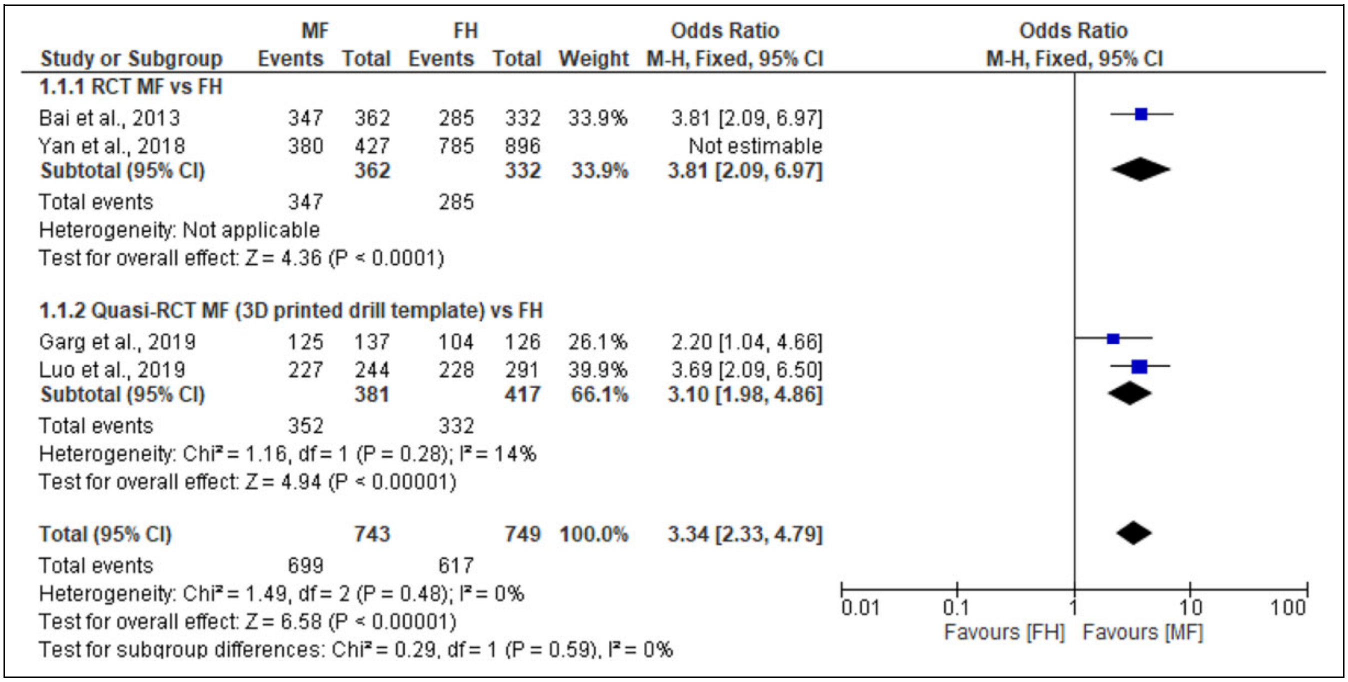

Figure 5. A meta-analysis of the accuracy of PS placement.

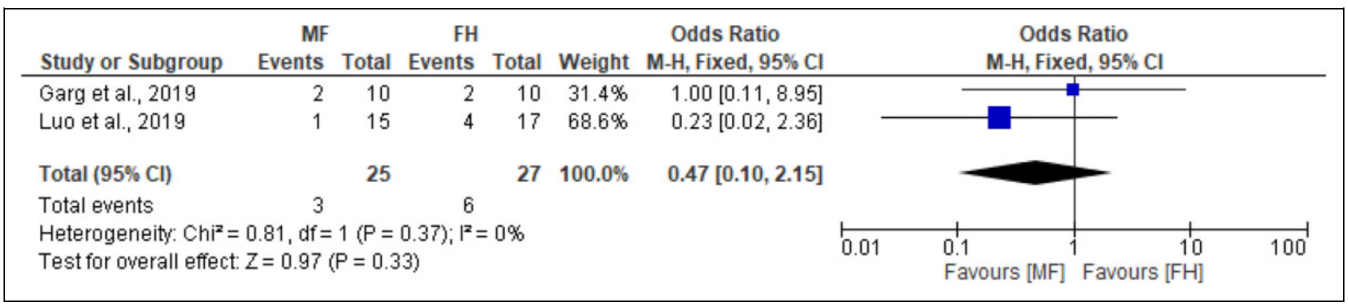

Figure 6. A meta-analysis of the postoperative complication rate.

placement in FH led to the development of intraoperative image-guided surgery, with FL and CT-nav as the 2 most common methods practiced today. We identified 1 RCT comparing FL with MF using 3D printed anatomic model. Interestingly, the accuracy of MF was significantly higher than FL (93.5% versus 84.7%, OR 2.59 (95% CI, 1.55-4.33), $P = .0003$).[8] The 3D printed model represents a better visualization of the deformed vertebrae because the surgeon can understand the anatomy in 3D physical format and plan the surgery better preoperatively. Furthermore, the surgeon can use the model intraoperatively side-by-side with the actual spine being operated on to give better visualization.[33] Meanwhile, FL mostly used 2-dimensional navigation, which only provides flat images in several projections.[34]

Our evidence supports the benefit of CT-nav in increasing PS placement accuracy (94.08% accuracy rate in CT-nav compared to 86.39% accuracy rate in FH, OR 2.50 (95% CI, 1.15-5.44), $P = .02$).[25] A meta-analysis by Tian et al. showed that the pedicle breach in CT-nav group was lower than those in FH group (OR 0.44 (95% CI, 0.32-0.60), $P < .01$).[35] A more recent meta-analysis from moderate evidence of 2 head-to-head comparative studies comparing CT-nav and FH in AIS surgery also found that CT-nav reduced pedicle breach (OR 0.28 (95% CI, 0.20-0.40, $I^2 = 1\%$), $P < .00001$).[36] When compared to other methods (RA, FL, and FH), CT-nav gave the highest accuracy (90.5%, 91.5%, 93.1%, and 95.5%, respectively).[37]

However, a high incidence of AIS caused substantial concern with the susceptibility of this age group when exposed to the ionizing radiation from FL or CT-nav. Cells in children are more vulnerable to radiation, as they have higher cell division rates than adults, and also they have more time to turn malignant after the initial damage from radiation.[38] Researchers have reported a greater incidence of malignancy in people who received ionizing radiation during childhood.[39-41] We define modified freehand (MF) as a group of methods to assist PS placement without the use of image-guidance (and non-ionizing) technologies. In this meta-analysis, MF showed a statistically significant higher accuracy

Certainty assessment							Summary of findings				
							Study event rates (%)			Anticipated absolute effects	
Participants (studies) Follow up	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Overall certainty of evidence	With conventional freehand	With Modified freehand	Relative effect (95% CI)	Risk with conventional freehand	Risk difference with Modified freehand
Accuracy of pedicle screws placement											
1492 pedicle screws (3 trials)	serious [a]	not serious	not serious	not serious	publication bias strongly suspected [b]	⊕⊕◯◯ LOW	617/749 (82.4%)	699/743 (94.1%)	**OR 3.34** (2.33 to 4.79)	824 per 1,000	**116 more per 1,000** (from 92 more to 133 more)
Complication rate											
52 patients (2 trials)	serious [a]	not serious	not serious	serious [c]	publication bias strongly suspected [b]	⊕◯◯◯ VERY LOW	6/27 (22.2%)	3/25 (12.0%)	**OR 0.47** (0.10 to 2.15)	222 per 1,000	**104 fewer per 1,000** (from 194 fewer to 158 more)

CI: Confidence interval; **OR:** Odds ratio

Explanations
a. Some aspects of the signalling questions in risk of bias assessment could not be answered due to insufficient information available. Therefore, there might be some potential for bias
b. Funnel plot analysis for reporting bias could not be conducted as less than 10 studies were included in the meta-analysis.
c. Low sample sizes

GRADE Working Group grades of evidence
High certainty: Further research is very unlikely to change our confidence in the estimate of effect.
Moderate certainty: Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate.
Low certainty: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate.
Very low certainty: We are very uncertain about the estimate.

Figure 7. Summary of findings and level of evidence of this review.

compared to FH (OR 3.34 (95% CI, 2.33-4.79), $P < .00001$). In the subgroup analysis, the screw placement with MF using 3D printed drill template was more accurate than FH (OR 3.10 (95% CI, 1.98-4.86), $P < .00001$).

Our present finding is in line with a meta-analysis by Fan et al. that revealed 3D printed drill template increased in vivo PS placement significantly compared to FH (OR 4.01 (95% CI, 2.49-6.44), $P < .0001$).[42] Similar results were also demonstrated by another meta-analysis of rapid prototyping drill navigation template-assisted PS fixation versus FH (OR 5.05, 95% CI (3.13-8.16), $P < .00001$).[43] To our knowledge, our review is the first meta-analysis comparing the accuracy of 3D printed drill template to FH for PS placement in pediatrics and adolescents spinal fusion surgery. Although the present review could not compare the surgical time and radiation exposure due to insufficient data, another meta-analysis has shown that 3D printed drill template also reduced radiation exposure times and surgical time in difficult cases.[42]

The subgroup analysis showed better accuracy in MF (with ECD) compared to FH (OR 3.81 (95% CI, 2.09-6.97), $P < .0001$). Varying results exist in the literature regarding ECD application. Chaput et al. compared 78 PS inserted with ECD assistance in 18 patients aged 55 ± 12 years. They found no difference in terms of accuracy; however, it is challenging to investigate the source of this distinct result as they did not elaborate the characteristics of the patients included in the surgery.[44] Greater benefit from this technology might be obtained in more complicated cases. A retrospective comparative study of 248 children with severe spinal deformities showed that in the ECD group there were less misplaced screws compared to the group without the aid of ECD (3.06% and 6.6% breach rates respectively, $P = .048$).[45]

Publications relating FPA technique or power drill in spinal surgery is limited. The literature showed that power drill system does not seem to affect the accuracy nor the surgery time compared to FH.[11,46] The RCT conducted by Yan et al. was judged as having a high risk of bias due to the different outcome measurement. They used 5 mm CT scan thickness to evaluate the spine; whereas thin-cut slices (approximately 1 mm) were recommended for precise bone evaluation after spinal surgery. The thinner the slices were, the less image noise presented; thus, the more sensitivity and specificity they produced.[26,47] Moreover, the FPA system did not seem to have a direct effect on improving pedicle screw accuracy. No specialized technology in the drilling tool functions to detect or reduce pedicle breach. Therefore, we excluded the evidence from our meta-analysis.

In the present review, we could not identify any trials using EMG, UG, or RA. A meta-analysis recommended that EMG should not be used independently to detect pedicle breach; instead, it should be combined with other measures as EMG may lead to false-negatives.[48] Meanwhile, UG seems to be still limited to experimental studies in phantoms, animals and human cadavers. Thus, more research is needed before the application in a clinical context.[49] RA is a novel technology with high cost, and the attempts to reduce its radiation exposure is still in its early development, limiting its widespread application.[50,51]

Complications and revision surgery rates. Not all misplaced screws led to complications and revision surgery. The complications rate among trials was low (5.84% of the total patients). The majority of the complications was related to neurovascular injury (82.35%), and the remaining was due to infection. No major vascular injury was reported. Nearly all complications were treated conservatively, resulting in patients' full recovery. However, in 2 patients with pre-existing preoperative cord compromise who developed complete cord injuries, no information was available regarding their recovery.[8] Moreover, one patient needed an emergency pedicle screw removal due to nerve compression.[9] Overall, the revision surgery rate was 0.34%, and no death was reported.

Our evidence showed an insignificant reduction of complications in patients operated with MF (3D printed drill guide) compared to FH (OR 0.47 (95% CI, 0.10-2.15), $P = .33$). A recent meta-analysis comparing the complications between 3D printed drill guide and conventional freehand in all age group also found no significant difference between the 2 methods (WRD = -0.04 (95% CI, -0.12 to 0.03), $P = .27$).[52] To our knowledge, our present review is the first to compare the complication rate between 3D printed drill guide and FH in pediatrics and adolescents.

As for image-guided surgery, a recent meta-analysis comparing image-guided surgery and FH in AIS reported conflicting complication rates (0-1.6% for image-guided and 0-1.7% for conventional freehand) due to low sample sizes.[36] Hicks et al. conducted a systematic review comprising 21 studies of a total of 4570 pedicle screws in 1666 patients in pediatrics and adolescents. Although they found 15.7% malposition screws rate, only 0.6% of the patients needed revision surgeries for screw removal.[3] Therefore, the pedicle screw placement is generally a safe procedure with low complication and revision surgery rates.

Strengths and Limitations

Limited high-quality clinical trials were available in the literature, mostly arising from information insufficiency of the reports (due to word count limitation). Another limitation of this review is language restriction. Hence, the result of this review should be interpreted with caution. Moreover, the overall evidence quality (certainty) assessed with GRADE for PS accuracy was rated as low-quality; whereas, the complication rate was very low-quality evidence. Further research may have an impact on the confidence of our estimate of effect. However, we have provided the current best evidence regarding this topic.

The drafting of research question and methodology was conducted according to the principles of Cochrane review and PRISMA guidelines. We believe our literature search strategy was extensive and robust. Moreover, although most of the patients described in the evidence were suffering from severe scoliosis, there were no restrictions based on the etiology of the patients. Therefore, the result of the current review seems to be applicable in all pediatrics and adolescents needing PS placement in spinal fusion surgery.

Recommendations for Future Studies

To obtain a high-quality systematic review, firstly the primary research needs to be of high quality. Therefore, future directions should be focusing on improving the primary research, i.e. producing well-designed RCTs with low risk of bias. The trial author should register their protocols with detailed information and link them to the reports published. Researchers should use an adequate randomization method and allocation concealment, as well as using standardized outcome measurement. Also, the discrepancy of breach/misplaced screws definition across trials should be solved. Currently, there is no agreed consensus of PS breach grading system. Therefore, we suggest future studies to explore this area. Moreover, the future systematic review should consider using network meta-analysis to compare 3 or more comparisons in a single analysis.

Conclusion

The systematic review and meta-analysis evidence suggest that 3D printed drill template and electronic conductivity (which we defined together as "modified freehand" method) increase the accuracy of PS placement in pediatrics and adolescents spinal fusion surgery. Overall, the complications and revision surgery rates are low. PS placement with 3D printed drill guide has fewer complications compared to FH. Although the quality of the evidence for the accuracy is low and for the complication rate is very low, we have demonstrated that this review is the current best evidence regarding this issue.

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Supplemental Material

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