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), \(P < .0001\), \(I^2 = 0\%\)). Three-dimensional printed drill template (as part of MF) was more accurate than FH (OR 3.10 (95% CI, 1.98-4.86), \(P < .0001\), \(I^2 = 14\%\)). 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
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), robot-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 | • Patients diagnosed with adolescent idiopathic scoliosis (AIS) who were operated during their adulthood (over 25 years old at the time of surgery) |
| • Children and adolescents (up to 25 years old) with any spinal conditions requiring PS insertion | • Summaries, letters to editors, summaries of meetings, expert opinion, review, book chapter, study protocol, technical report |
| • Published and unpublished articles that were written in English and available in full-text | • Systematic reviews, meta-analyses |
| • No limitation on publication time                                                | • Observational studies |

We applied an RCT filter provided by PubMed for MEDLINE and the Scottish Intercollegiate Guidelines Network (SIGN) for EMBASE. 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. 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.

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. As for CCT, we used the Risk Of Bias In Non-randomized Studies-of Interventions (ROBINS-I) tool.

**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 \( \chi^2 \) and \( I^2 \) test. A low \( P \)-value (\( P < .1 \)) of \( \chi^2 \) test and an \( I^2 > 50\% \) indicate a substantial heterogeneity. 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. The assessment was performed using GRADEpro GDT, McMaster University & Evidence Prime, Inc.)
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).\textsuperscript{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
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. 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. 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. 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

Table 2. Characteristics of the Included Trials.

| No | Author       | Study design | Settings                       | Patients       | Indication of surgery | Cobb’s angle (mean) |
|----|--------------|--------------|--------------------------------|----------------|-----------------------|---------------------|
|    |              |              |                                |                |                       |                     |
| 1  | Bai et al., 2013 | RCT          | China                          | 9 33           | 0 42                  | E & C = 55.3° ± 7°  |
|    |              |              |                                |                |                       | (range 45-78°)     |
| 2  | Garg et al., 2019 | Quasi-RCT    | India, single center           | 7 13           | 11 7                  | E = 85.3° and C = 90.4° |
| 3  | Luo et al., 2019 | CCT          | China, June 2016-June 2018, single center | 11 21         | 32 0                  | E = 113° ± 15° and C = 106° ± 14° |
| 4  | Su et al., 2012 | RCT          | China, 2006-2008, single center | 7 13           | 0 20                  | 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                  | E = 85° and C = 75° |
| 6  | Yan et al., 2018 | RCT          | China, June 2014-June 2015, single center | 34 71         | 0 105                 | 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.
the cut-off for safe zone. We intended to reclassify the breach based on 2 mm increment as recommended by a systematic review; 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”). 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 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. 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. Finally, we conducted a meta-analysis comparing the accuracy of the PS placement involving 3 trials (OR 3.34 (95% CI, 2.33-4.79), P < .00001, I² = 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, I² = 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. 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, while the highest accuracy was 95.86% seen in MF using ECD. In the meta-analysis, we included 3 trials with matching head-to-head comparisons (MF versus FH). 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 Chi² test showed a high P-value (.28) and I² = 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. Two trials used rapid prototyping technology in the form of 3D printed drill template. The meta-analysis showed increased accuracy of PS when placed with MF (OR 3.34 (95% CI, 2.33-4.79), P < .00001, I² = 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. Being female increased the chance of developing scoliosis by 4.7 times with the peak incidence was found during puberty (13-14 years old). Some researchers have identified genetic roles in scoliosis and curve progression, with female was known to have a 10-fold higher risk of curve progression. Although hormonal disturbance during puberty and mutation in estrogen receptors genes were suspected to be the cause, a recent meta-analysis showed the contrary. 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 | Total patients | Postoperative complications | Odds ratio (95% CI), test for overall effect (P-value) | Treatment |
|----|--------|--------------------------------------|--------------------|-----------------|-----------------|----------------|----------------------------|-------------------------------------------------|-----------|
| 1  | Bai et al., 2013 | MF (Electronic conductivity) | 362                | 347             | 15              | 20            | 0                          | 3.18 (1.81-5.60), P < .001 | 0         |
| 2  | Garg et al., 2019 | FH | 332                | 285             | 47              | 22            | 0                          | 2.20 (1.04-4.66), P = .04 | 0         |
| 3  | Luo et al., 2019 | MF (3D printed drill guide) | 244                | 227             | 17              | 15            | 1                          | 3.69 (2.09-6.50), P < .00001 | Sodium aescinate (anti-inflammatory agent), mouse nerve growth factor (reduces myelin edema) |
| 4  | Su et al., 2012   | CT-nav | 169                | 159             | 10              | 10            | 0                          | 2.50 (1.15-5.44), P = .02 | 0         |
| 5  | Wu et al., 2011   | FH | 383                | 358             | 23              | 34            | 0                          | 2.59 (1.55-4.33), P = .0003 | Patients recovered after 3-6 months of conservative treatment |
| 6  | Yan et al., 2018   | FH | 896                | 785             | 111             | 70            | 0                          | 1.14 (0.80-1.64), P = .47 | 0         |

FH: Conventional Freehand; MF: Modified Freehand; CT-nav: CT-based navigation; FL: Fluoroscopy-based navigation.
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), \( P = .0003 \)). 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. Meanwhile, FL mostly used 2-dimensional navigation, which only provides flat images in several projections.

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, 1.55-4.44), \( P = .02 \)). 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), \( P < .01 \)). 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, \( I^2 = 1\% \)), \( P < .00001 \)). 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).

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. Researchers have reported a greater incidence of malignancy in people who received ionizing radiation during childhood. 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.
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), \( P < .0001 \)).\(^4^2\) 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), \( P < .00001 \)).\(^4^3\) 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.\(^4^2\)

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.\(^4^4\) 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, \( P = .048 \)).\(^4^5\)

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.\(^1^1,^4^6\) 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.\(^2^6,^4^7\) 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. 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. 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.

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. Moreover, one patient needed an emergency pedicle screw removal due to nerve compression. 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), \( P = .27 \)). 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. 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. 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**

Supplemental material for this article is available online.

**References**

1. Roy-Camille R, Roy-Camille M, Delemoulaere C. Osteosynthesis of dorsal, lumbar, and lumbosacral spine with metallic plates screwed into vertebral pedicles and articular apophyses [in French]. Presse Med. 1970;78(32):1447-1448. Ostéosynthèse du rachis dorsal, lombaire et lombo-sacré par plaques métalliques vissées dans les pédicules vertébraux et les apophyses articulaires.

2. Dubousset J. Past, present, and future in pediatric spinal surgery. Ann Transl Med. 2020;8(2):36. doi:10.21037/amt.2019.08.13

3. Hicks JM, Singla A, Shen FH, Arlet V. Complications of pedicle screw fixation in scoliosis surgery: a systematic review. Spine (Phila Pa 1976). 2010;35(11):E465-E470. doi:10.1097/BRS.0b013e3181d021a

4. Sarwahi V, Suggs W, Wollowick AL, et al. Pedicle screws adjacent to the great vessels or viscera: a study of 2132 pedicle screws in pediatric spine deformity. J Spinal Disord Tech. 2014;27(2):64-69. doi:10.1097/BSD.0b013e31825bfecd

5. Larson AN, Santos ER, Polly DW Jr, et al. Pedicle screw placement using intraoperative computed tomography and 3-dimensional image-guided navigation. Spine (Phila Pa 1976). 2012;37(3):E188-E194. doi:10.1097/BRS.0b013e31822a2e0a

6. Zhu F, Sun X, Qiao J, Ding Y, Zhang B, Qiu Y. Misplacement pattern of pedicle screws in pediatric patients with spinal deformity: a computed tomography study. J Spinal Disord Tech. 2014;27(8):431-435. doi:10.1097/BSD.0b013e31828d6a1b

7. Perna F, Borghi R, Pilla F, Stefanini N, Mazzotti A, Chehrassan M. Pedicle screw insertion techniques: an update and review of the literature. Musculoskelet Surg. 2016;100(3):165-169. doi:10.1007/s12306-016-0438-8

8. Wu ZX, Huang LY, Sang HX, et al. Accuracy and safety assessment of pedicle screw placement using the rapid prototyping technique in severe congenital scoliosis. J Spinal Disord Tech. 2011;24(7):444-450. doi:10.1097/BSD.0b013e318201be2a

9. Luo M, Wang W, Yang N, Xia L. Does Three-dimensional printing plus pedicle guider technology in severe congenital scoliosis facilitate accurate and efficient pedicle screw placement? Clin Orthop Relat Res. 2019;477(8):1904-1912. doi:10.1097/corr.0000000000000739

10. Bai YS, Niu YF, Chen ZQ, et al. Comparison of the pedicle screws placement between electronic conductivity device and normal pedicle finder in posterior surgery of scoliosis. Clinical Spine Surgery. 2013;26(6):316-320.

11. Yan H, Jiang D, Xu L, et al. Does the full power-assisted technique used in pedical screw placement affect the safety and efficacy of adolescent idiopathic scoliosis surgery? World Neurosurg. 2018;116:e79-e85. doi:10.1016/j.wneu.2018.04.047

12. Duffy MF, Phillips JH, Knapp DR, Herrera-Soto JA. Usefulness of electromyography compared to computed tomography scans in pedicle screw placement. Spine (Phila Pa 1976). 2010;35(2):E43-E48. doi:10.1097/BRS.0b013e3181b3f467

13. Bourgeois AC, Faulkner AR, Pasciak AS, Bradley YC. The evolution of image-guided lumbosacral spine surgery. Ann Transl Med. 2015;3(5):69-69. doi:10.3978/j.issn.2305-5839.2015.02.01

14. Kantelhardt SR, Bock CH, Larsen J, et al. Intraoperative ultrasound in the placement of pedicle screws in the lumbar spine. Spine (Phila Pa 1976). 2009;34(4):400-407. doi:10.1097/BRS.0b013e31819286ca

15. Higgins J, Thomas J, Chandler J, et al. Cochrane Handbook for Systematic Reviews of Interventions version 6.0. Updated July 2019. Accessed June 18, 2020. www.training.cochrane.org/handbook

16. Liberati A, Altman DG, Tetzlaff J, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ. 2009;339:b2700. doi:10.1136/bmj.b2700

17. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339:b2535. doi:10.1136/bmj.b2535

18. SIGN. Search Filters. 2019. Accessed May 13, 2020. https://www.sign.ac.uk/search-filters

19. Ouzzani M, Hammad H, Fedorowicz Z, Elmagarmid A. Rayyan—a web and mobile app for systematic reviews. Syst Rev. 2016;5(1):210. doi:10.1186/s13643-016-0384-4

20. Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. BMJ. 2019;366:l4898. doi:10.1136/bmj.l4898

21. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ. 2016;355:i4919. doi:10.1136/bmj.i4919

22. Deeks J, Higgins J, Altman D. Analysing data and undertaking meta-analyses. In: Higgins J, Thomas J, Chandler J, et al, eds. Cochrane Handbook for Systematic Reviews of Interventions version 6.0. 2019. Chapter 10. www.training.cochrane.org/handbook

23. Schünemann H, Higgins J, Vist G, et al. Completing ‘Summary of findings’ tables and grading the certainty of the evidence. In: Higgins J, Thomas J, Chandler J, et al, eds. Cochrane Handbook for Systematic Reviews of Interventions version 60. 2019. Chapter 6. www.training.cochrane.org/handbook

24. Garg B, Gupta M, Singh M, Kalyanasundaram D. Outcome and safety analysis of 3D-printed patient-specific pedicle screw jigs for complex spinal deformities: a comparative study. Spine J. 2019;19(1):56-64. doi:10.1016/j.spinee.2018.05.001

25. Su P, Zhang W, Peng Y, Liang A, Du K, Huang D. Use of computed tomographic reconstruction to establish the ideal entry point for pedicle screws in idiopathic scoliosis. Eur Spine J. 2012;21(1):23-30. doi:10.1007/s00586-011-1962-8

26. Ho JM, Ben-Galim PJ, Weiner BK, et al. Toward the establishment of optimal computed tomographic parameters for the
assessment of lumbar spinal fusion. Spine J. 2011;11(7):636-640. doi.org/10.1016/j.spinee.2011.04.027

27. Aoude AA, Fortin M, Figueiredo R, Jarzem P, Ouellet J, Weber MH. Methods to determine pedicle screw placement accuracy in spine surgery: a systematic review. Eur Spine J. 2015;24(5):990-1004. doi:10.1007/s00586-015-3853-x

28. Zhang W, Takigawa T, Wu Y, Sugimoto Y, Tanaka M, Ozaki T. Accuracy of pedicle screw insertion in posterior scoliosis surgery: a comparison between intraoperative navigation and preoperative navigation techniques. Eur Spine J. 2017;26(6):1756-1764. doi:10.1007/s00586-016-4930-5

29. Penha PJ, Ramos N, de Carvalho BKG, Andrade RM, Schmitt ACB, João SMA. Prevalence of adolescent idiopathic scoliosis: diagnosis and management. Am Fam Physician. 2014;89(3):193-198.

30. Zhao L, Roffey DM, Chen S. Association between the Estrogen Receptor Beta (ESR2) Rs1256120 single nucleotide polymorphism and adolescent idiopathic scoliosis: a systematic review and meta-analysis. Spine (Phila Pa 1976). 2018;43(24):1710-1718. doi:10.1097/BRS.0000000000002725

31. Horne JP, Flannery R, Usman S. Adolescent idiopathic scoliosis and genetic testing. Curr Opin Pediatr. Feb 2010;22(1):67-70. doi:10.1097/MOP.0b013e32833419ac

32. Penha PJ, Ramos N, de Carvalho BKG, Andrade RM, Schmitt ACB, Joa˜o SMA. Prevalence of adolescent idiopathic scoliosis in the state of São Paulo, Brazil. Spine (Phila Pa 1976). 2018;43(24):1710-1718. doi:10.1097/BRS.0000000000002725

33. Ogilvie J. Adolescent idiopathic scoliosis and genetic testing. Curr Opin Pediatr. Feb 2010;22(1):67-70. doi:10.1097/MOP.0b013e32833419ac

34. Du JP, Fan Y, Wu QN, Wang DH, Zhang J, Hao DJ. Accuracy of pedicle screw insertion in posterior scoliosis surgery: a systematic review and meta-analysis of comparative studies. Eur Spine J. 2011;20(6):1002-1004. doi:10.1007/s00586-010-1577-5

35. Tian NF, Huang QS, Zhou P, et al. Pedicle screw insertion accuracy with different assisted methods: a systematic review and meta-analysis of comparative studies. Eur Spine J. 2011;20(6):846-859. doi:10.1007/s00586-010-1577-5

36. Chan A, Parent E, Wong J, Narvacan K, San C, Lou E. Does image guidance decrease pedicle screw-related complications in surgical treatment of adolescent idiopathic scoliosis: a systematic review update and meta-analysis. Eur Spine J. 2020;29(4):694-716. doi:10.1007/s00586-019-06219-3

37. Perdomo-Pantoja A, Ishida W, Zygiourakis C, et al. Accuracy of current techniques for placement of pedicle screws in the spine: a comprehensive systematic review and meta-analysis of 51,161 screws. World Neurosurg. 2019;126:664-678.e3. doi:10.1016/j.wneu.2019.02.217

38. Schenkman L. Radiology. Second thoughts about CT imaging. Science. 2011;331(6020):1002-1004. doi:10.1126/science.331.6020.1002

39. Mathews JD, Forsythe AV, Brady Z, et al. Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. BMJ. 2013;346:f2360. doi:10.1136/bmj.f2360

40. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. Lancet. 2012;380(9840):499-505. doi:10.1016/s0140-6736(12)60815-0

41. Dobson GM, Dalton AK, Nicholson CL, Jenkins AJ, Mitchell PB, Cowie CJA. CT scan exposure in children with ventriculoperitoneal shunts: single centre experience and review of the literature. Childs Nerv Syst. 2020;36(3):591-599. doi:10.1007/s00381-019-04345-3

42. Fan Y, Du JP, Wu QN, Zhang JN, Hao DJ. Accuracy of a patient-specific template for pedicle screw placement compared with a conventional method: a meta-analysis. Arch Orthop Trauma Surg. 2017;137(12):1641-1649. doi:10.1007/s00402-017-2815-7

43. Wen ZJ, Gao ZC, Lu T, Wang YB, Liang H, He XJ. Comparison of the effect of navigation template assisted spinal pedicle fixation and traditional pedicle screw fixation: a meta-analysis [in Chinese]. Zhongguo Gu Shang. 2018;31(11):1069-1076. doi:10.3969/j.issn.1003-0034.2018.11.017

44. Chaput CD, George K, Samdani AF, Williams JI, Gaughan J, Betz RR. Reduction in radiation (fluoroscopy) while maintaining safe placement of pedicle screws during lumbar spine fusion. Spine (Phila Pa 1976). 2012;37(21):E1305-E1309. doi:10.1097/BRS.0b013e182666adc

45. Ovadia D, Korn A, Fishkin M, Steinberg DM, Wientroub S, Ofiram E. The contribution of an electronic conductivity device to the safety of pedicle screw insertion in scoliosis surgery. Spine (Phila Pa 1976). 2011;36(20):E1314-E1321. doi:10.1097/BRS.0b013e1822a88ec

46. Sehauser DA, Skaggs DL, Andras LM, Javidan Y. Safety and efficacy of power-assisted pedicle tract preparation and screw placement. Spine Deform. 2015;3(2):159-165. doi:10.1016/j.jspd.2014.07.001

47. Alshipili M, Kabir NA. Effect of slice thickness on image noise and diagnostic content of single-source-dual energy computed tomography. J Phy Con Ser. 2017;851:012005. doi:10.1088/1742-6596/851/1/012005

48. Oner A, Ely CG, Hermsmeyer JT, Norvell DC. Effectiveness of EMG use in pedicle screw placement for thoracic spinal deformities. Evid Based Spine Care J. 2012;3(1):35-43. doi:10.1055/s-0031-1298599

49. Chan A, Coutts B, Parent E, Lou E. Development and evaluation of CT-to-3D ultrasound image registration algorithm in vertebral phantom for spine surgery. Ann Biomed Eng. 2020;49(1):310-321. doi:10.1007/s10439-020-02546-5

50. Sennakovic WF, O’Dell MC, Agha A, Woo R, Varich L. CT radiation dose reduction in robot-assisted pediatric spinal surgery. Spine (Phila Pa 1976). 2017;42(7):E417-E424. doi:10.1097/BRS.0000000000001846

51. Cawley DT, Rajamani V, Cawley M, Selvadurai S, Gibson A, Cawley DT. Using lean principles to introduce intraoperative navigation for scoliosis surgery. Bone Joint J. 2020;102-B(1):5-10. doi:10.1302/0302-6736(2020)102-B(J)-05-01

52. Wallace N, Butt BB, Aleem I, Patel R. Three-dimensional printed drill guides versus fluoroscopic-guided freehand technique for pedicle screw placement: a systematic review and meta-analysis of radiographic, operative, and clinical outcomes. Clin Spine Surg. 2020;33(8):314-322. doi:10.1097/BSD.0000000000001023