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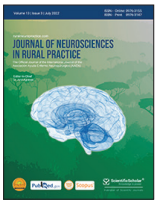

Systematic Review

Positioning accuracy and facet joints violation after percutaneous pedicle screws placement with robot-assisted versus fluoroscopy-guided technique: Systematic review and meta-analysis

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ABSTRACT

Introduction: Minimally invasive spine surgery became the gold standard for the treatment of many spinal diseases. Only a few comparative studies were performed regarding the superiority of robotic-assisted (RA) surgery over fluoroscopic guidance (FG) surgery during percutaneous pedicle screws placement. Therefore, the aim of the present study was to conduct a systematic literature review and meta-analysis to evaluate the accuracy and potential advantages of RA compared with FG.

Material and Methods: This study is a systematic literature review conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines. The review questions were formulated following the PICO scheme. Measured outcomes were presented using Forest plots. Heterogeneity among the included studies was assessed using the χ^2 test, and the I^2 statistic was utilized to estimate the proportion of total variation among the studies. A value exceeding 50% was considered indicative of substantial heterogeneity.

Results: Seven studies that met inclusion criteria were finally included in this meta-analysis. These seven studies include: 447 patients, 228 patients (931 screws) treated with robotic guide, and 219 patients (767 pedicle screws) using fluoroscopic guide, with a mean age of 55.2. The percentages of clinically acceptable screws were 94.3% in the robot-assisted group and 89% in the fluoroscopic guided group. The percentages of non-acceptable screws were 5.7% in the robot-assisted group and 11% in the fluoroscopic-guided group.

Discussion: Significant differences were observed between the two groups in terms of radiographic and clinical outcomes, with the robotic-assisted pedicle screw group exhibiting longer operative times. Robot technology serves as a valuable tool for assisting surgeons in challenging scenarios such as anatomical variants or patients with spinal deformities, ensuring accurate screw placement.

Conclusion: The accuracy of pedicle screw placement with robotic technology is higher than with FG. In fact, the robotic approach allows significantly lower complication rates, fewer cases of violation of the proximal articular facet, less intraoperative exposure to radiation, even if it requires longer surgical times than the FG technique.

Keywords: Minimally invasive spine surgery, Robotic assisted spinal surgery, Percutaneous pedicle screws

INTRODUCTION

Minimally invasive spine surgery (MISS) has become the standard treatment for various spinal conditions.[1] It offers well-documented advantages.[2-4] Percutaneous pedicle screw (PPS) placement is a widely used, safe, and effective method for posterior column fixation during MISS.[5] While traditionally guided by fluoroscopic guidance (FG), PPS placement can lead to complications such as pedicle breach or facet joint violation (FJV).[5] Accurate screw placement is essential to avoid damage to nearby structures and ensure stability.[6] Conventional techniques have reported misplacement rates ranging from 5% to 41% for lumbar and 355% for thoracic spine, influenced by factors such as surgeon experience and patient positioning.[7] In recent years, many technological aids such as neuronavigation and robotic-assisted (RA) surgery could help the surgeon during pedicle screw placement with the attempt to standardize this procedure.[1] Cadaveric and clinical studies on RA surgery claimed for an high-accuracy and minor intraoperative

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radiation exposure, over conventional methods during pedicle screws placement in spinal fusions.[2-5]

However, recent meta-analysis evaluated this controversial issue and concluded that the superiority of RA over conventional methods regarding screw placement accuracy was indefinite.[2,3] Only a few comparative studies were performed regarding the superiority of RA surgery over FG surgery during PPS placement. Therefore, the aim of the present study was to conduct a systematic literature review and meta-analysis to evaluate the accuracy and potential advantages of RA compared with FG.

MATERIALS AND METHODS

Study setting and search strategy

The present study is a systematic literature review that adheres to the Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines [Figure 1].[8] A comprehensive electronic search was conducted on Scopus, Cochrane Library, and MEDLINE through the PubMed database. Various combinations of keywords such as "robot," "robotic," "robotics," "percutaneous," "pedicle screw," "Spine," and "Spinal," along with their MeSH terms, were used in the search, employing logical operators "AND" and "OR." Furthermore, relevant studies were identified by screening the reference lists. The search was repeated until March 14, 2022. The review protocol was initiated on March 7, 2022, and registered with the International Prospective Register of Systematic Reviews (PROSPERO), ID: CRD42022316761.

Inclusion and exclusion criteria

In the present review, only the full-text English written articles reporting comparisons between RA and FG screws placement for degenerative, traumatic, and infective disease were considered eligible. No date of publication limits was set.

Review question

The review questions were structured according to the PICO scheme,[9] which encompasses the population (P), intervention (I), comparison (C), and outcome (O). In this study, the formulated question is: "In patients with spinal disease (P), does robotic-assisted spinal surgery (I) yield superior radiological outcomes (accuracy of screw placement) (O) compared to percutaneous fluoroscopic-guided screws (C)?"

Data extraction

Screening of title and abstract was performed by two independent authors (A.S. and C.V.). Any discordances were solved by consensus with a third author (A.P). The data from the included articles were then collected by the same authors.

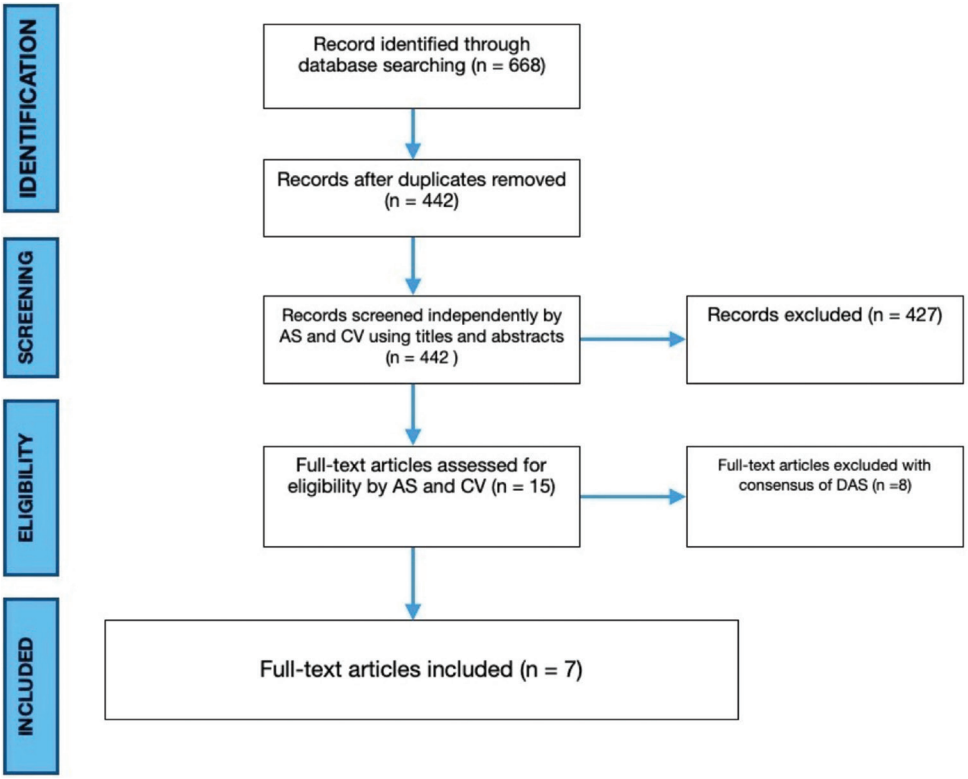

Figure 1: Preferred reporting items for systematic reviews and meta-analyses search strategy flow chart.

The following data were extracted: demographic features, level involved, radiation exposure, number of screws placed, intraoperative blood loss, operative time, length of stay, clinical and functional outcomes, possible complications, and follow-up.

Statistical analysis

Data tabulation was conducted using Numbers software (Cupertino, CA, Apple Inc.). Categorical variables were presented as percentages, while continuous variables were expressed as means and standard deviations. Measured outcomes were illustrated using Forest plots. Heterogeneity was assessed using the χ^2 test, and the I^2 statistic was utilized to estimate the extent of total variation, with a value above 50% indicating substantial heterogeneity. A random-effects model was employed when a large I^2 value was obtained, while a fixed-effects model was used otherwise. The quality of the included studies was evaluated using the Cochrane Collaboration's Tool [Figure 2].

Statistical analysis and the generation of Forest plots were performed using Review Manager Version 5.4.1 (Cochrane Collaboration, Software Update, Oxford, United Kingdom).

RESULTS

Study selection

After the screening of 668 titles and abstracts, (442 after screening duplicates) 15 papers were considered eligible for the full-text analysis. Seven studies that met inclusion criteria were finally included in this meta-analysis.

These seven studies include 447 patients, 228 patients (931 screws) treated with robotic guide and 219 patients (767 pedicle screws) using the fluoroscopic guide, with a mean age of 55.2.

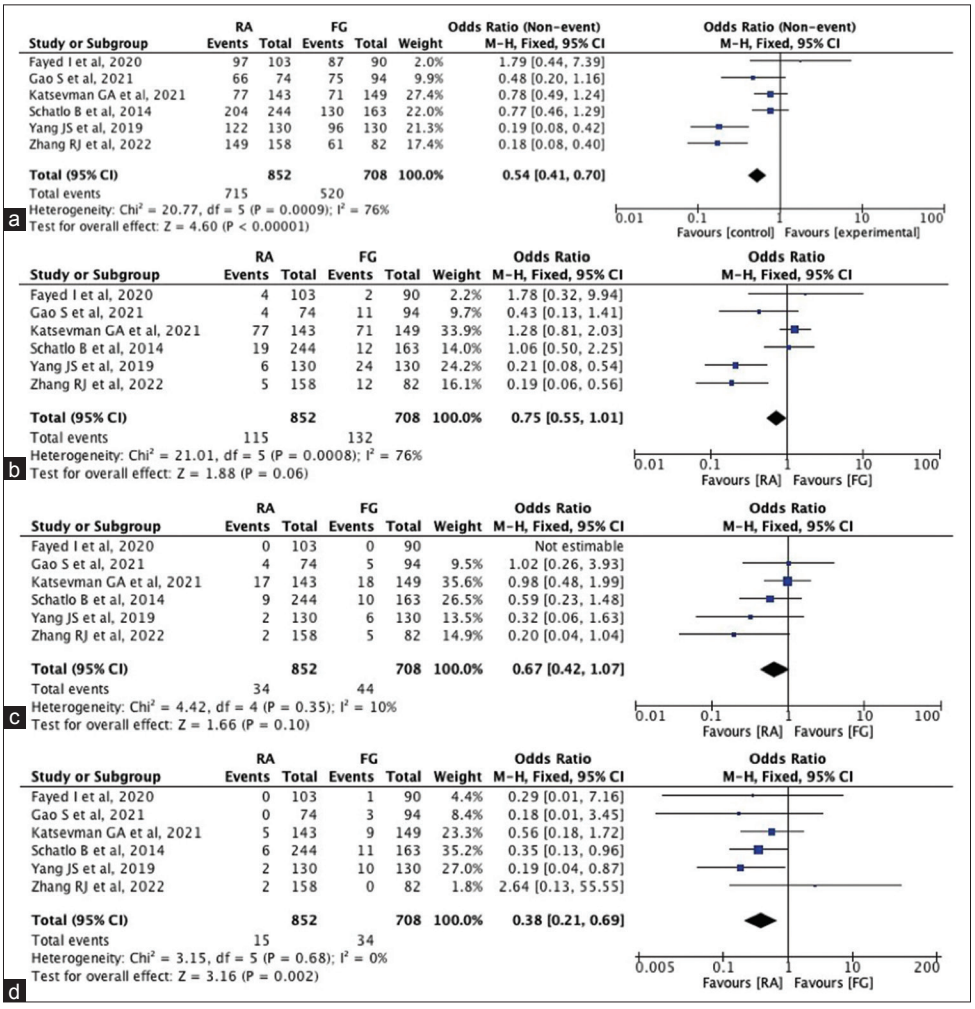

Figure 2: The Cochrane risk of bias tool was utilized to assess bias in the included studies. Bias was evaluated across various domains, including selection, performance, detection, attrition, reporting, and other factors. Each domain was categorized as low risk (green), unclear risk (yellow), or high risk (red).

The indications for surgery across the different studies were either traumatic fractures or degenerative diseases. The surgery was performed at all levels and we did not exclude any particular level.

Screw accuracy placement

The most common classification system used in literature is Gebertzbein-Robbins classification. Over seven studies included all authors provided accuracy data, but Archavlis *et al.*,[6] (1560 screws, 852 with robotic guide, and 708 with fluoroscopic guide) using computed tomography (CT) scan for grading post-operative accuracy, only Gao *et al.* also used MRI.[7] According to Gebertzbein-Robbins, the screws placed with optimal intrapedicular accuracy (Grade A ≤0 mm) in the RA group were 715 (83.92%), while 520 in the FG group (73.44%). The meta-analysis of these data showed an odds ratio of 0.54 (95% confidence interval [CI], 0.41–0.70; $P < 0.001$), showing a decreasing odd of screw inaccuracy in the RA group compared to FG [Figure 3a]. According to Grade B (≤2 mm), 82 screws were placed in the RA group (9.62%) and 112 in FG group (15.82%). The meta-analysis of the data revealed a mean difference of 0.75 (95% CI, 0.55–1.01; $P = 0.06$) [Figure 3b]. Moreover, 34 screws (3.99%) were placed in the first group with an intrapedicular accuracy of 2–4 mm (Grade C), while 44 (6.21%) in the second one. The meta-analysis of these data showed an odds ratio of 0.67 (95% CI, 0.42–1.07; $P = 0.10$) [Figure 3c]. Finally, 15 screws (Grade D+E) 1.76% were placed in the RA group, while 28 (3.95%) in the FG group. The meta-analysis of the data showed an odds ratio of 0.38 (95% CI, 0.21–0.69; $P = 0.002$) [Figure 3d]. The percentages of clinically acceptable screws (Gertzbein and Robbins Grades A and B) were 94.3% in the robot-assisted group and 89% in the fluoroscopic-guided group. The meta-analysis of these data showed an odds ratio of 0.56 (95% CI,

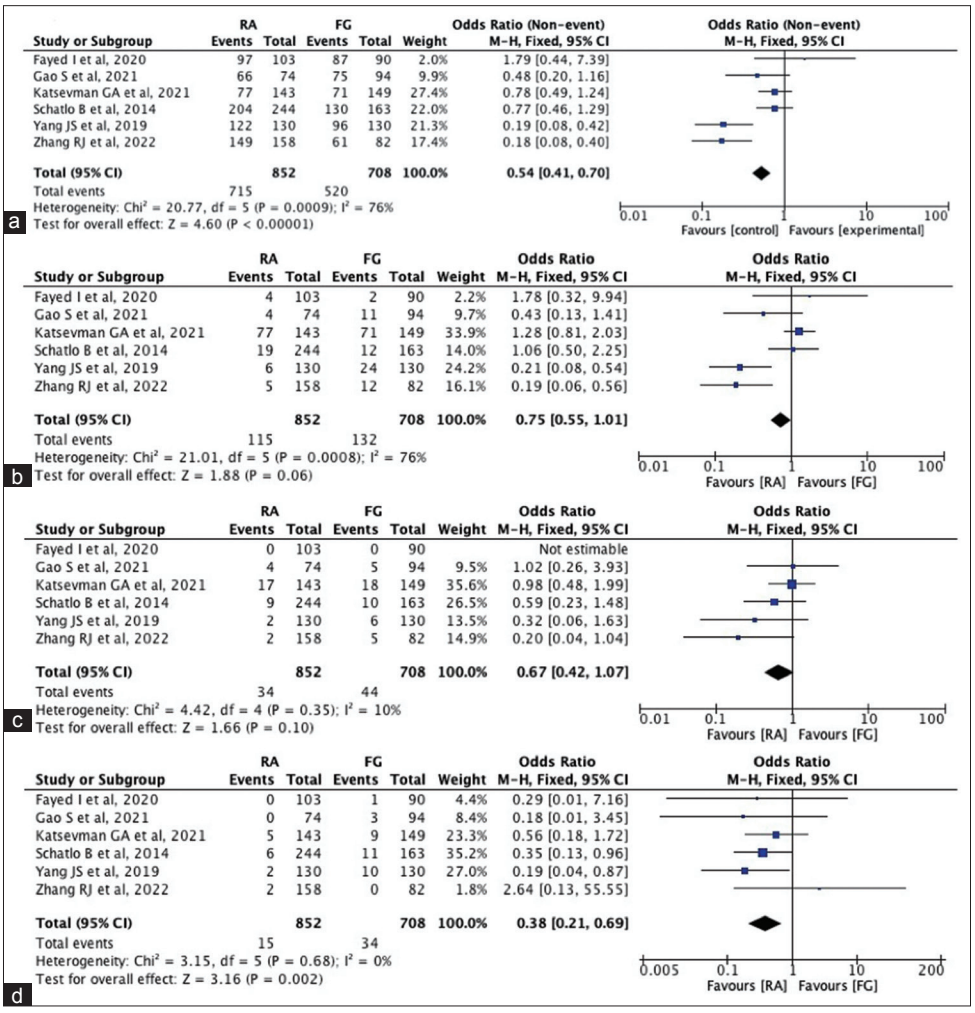

Figure 3: Forest plots comparing surgical outcomes between robotic assisted (RA) and fluoroscopic guidance (FG) surgery. (a) Screw accuracy placement Grade A according to Gebertzbein-Robbins, (b) Grade B, (c) Grade C, and (d) Grade D.

0.38–0.82; P = 0.003), showing a higher rate of clinically acceptable screws in the RA group compared to the FG group [Figure 4a]. The percentages of non-acceptable screws (Gertzbein and Robbins Grades C and D) were 5.7% in the robot-assisted group and 11% in the fluoroscopic-guided group. The meta-analysis of the data showed an odds ratio of 0.58 (95% CI, 0.40–0.84; P = 0.004), showing a reduced rate of non-acceptable screws in the RA group compared to the FG group [Figure 4b].

FJV

The grades of FJV were analyzed according to Babu scale. In the RA group, 503 screws (86.27%) (Grade 0) were placed without violation of the facet joint, while in the FG group 274 screws (70.98%). A total of 30 screws (5.14%) of the RA group were placed in lateral facet but not in facet articulation (Grade I), while 32 screws (8.29%) in the FG group. Twelve screws (2.05%) of the first group penetrated facet articulation <1 mm (Grade II), while 27 screws (6.99%) in the second one. Finally, only 6 screws (1.02%) in the RA group were placed traveling facet articulation (Grade III), while 15 screws (3.88%) in the FG group.

Radiation exposure, blood loss, operative time and complications

Only Zhang *et al.*[10] and Schatlo *et al.*[11] reported operative time and blood loss. In the RA group operative time was longer, but with no statistical difference between the groups (95% CI: 6.57–38.83, P = 0.006). Regarding blood loss in Zhang *et al.* study,[10] there were no differences between the two groups, however in Schatlo *et al.*[11] cases significantly lower in the robot group (Group I, 375 ± 263 min; Group II, 713 ± 455 [P < 0.01]).

DISCUSSION

Pedicle screw placement is the gold standard for many pathologies in spine surgery. Neuronavigation and RA surgery are a valid surgical assistance in many fields.[12] It is applied in MISS to increase intrapedicular accuracy, to reduce the cranial facet violation and the X-rays exposure of the surgeons.

To date, no evidence has shown the superiority of RA over FG technique in terms of intrapedicular accuracy and cranial facet joint protection.[16] Consequently, the purpose of this meta-analysis was to evaluate the incidence of PPS placement accuracy and cranial FJV between the RA and FG groups. Our findings reveal statistically significant differences in radiographic and clinical outcomes between these two groups.

In particular, we reported a higher percentage of clinically acceptable screws according to Gertzbein and Robbins (Grades A and B) in the RA group and also a lower percentage of non-acceptable screws (Grades C and D). Considering that there are many factors that could affect accuracy such as revision surgery, challenging anatomy, and surgeon experience, the robot may be advantageous in terms of accuracy thanks to a three dimensional visualization.[13] However, although the robotic systems have many mechanical tools which improve surgical precision,[8] the surgeon's sensibility and discretion are not to be considered inferior to the robot's accuracy.

Another important aspect is the Violation of Facet Joint that could be one of the consequences of an incorrect placement of pedicle screws,[17] which could lead to facet arthrosis, increase the adjacent level segment disease,[9,14] and avoidable neurological or vascular complications.

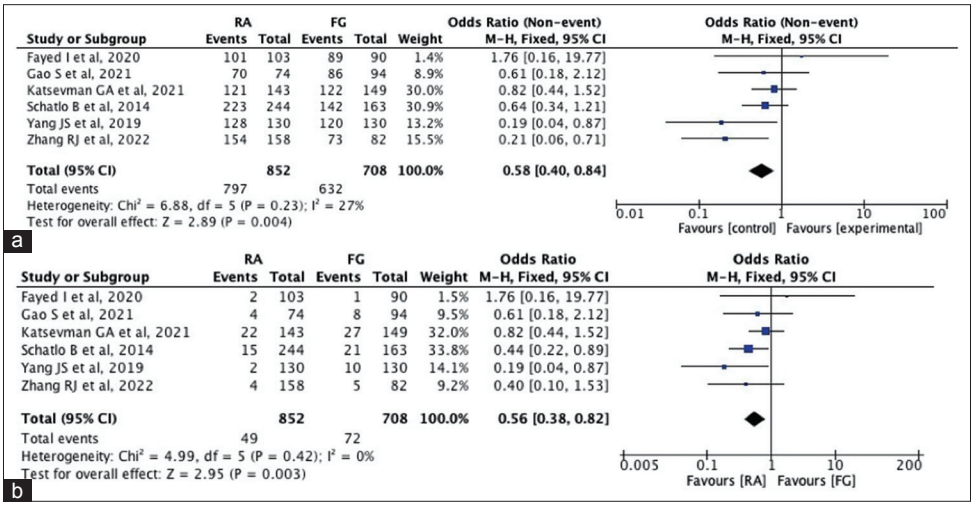

Figure 4: Forest plots comparing surgical outcomes between robotic assisted (RA) and fluoroscopic guidance (FG) surgery. (a) Clinically acceptable screws and (b) Clinically not acceptable screws.

According to the Babu scale, our findings suggest that RA surgery has fewer complications and proximal facet joint violations compared to the FG technique. This is likely due to the robotic system's 3D imaging acquisition, enabling surgeons to plan trajectories and avoid screw misplacements. However, accurate image acquisition and recording are crucial for this advantage. In contrast, the FG technique relies on anatomical landmarks and intraoperative fluoroscopic images, requiring the surgeon's visual intuition for trajectory visualization.[5,18]

Radiation exposure risks for operating room staff could not be adequately evaluated due to insufficient data in the eligible studies.[19] Nonetheless, robot-assisted surgery reduces reliance on intraoperative fluoroscopy compared to the included studies. Our results indicate significantly longer operative times for RA surgery compared to the FG technique, but this aspect may improve with surgeon experience in robotic technology.

This systematic review and meta-analysis demonstrate that robotic systems provide effective and safe options for PPS placement in spine surgery, offering promising advancements. However, it is important to acknowledge that introducing additional devices and technologies into the operating room increases the potential for errors.

Errors can occur during image acquisition, registration, and reference array motion, impacting the accuracy of robotic systems' navigation. The precision of these systems relies on computer software processing, and any inaccuracies may cause the robot to execute an erroneous plan. While such issues can be resolved in open spine surgery, where the surgeon can visually verify and adjust the robot's indicated screw entry point, minimally invasive percutaneous surgery poses challenges. Surgeons have limited anatomical visualization and rely heavily on three-dimensional images provided by navigation or FG.

Moreover, the cost efficiency of RA spine surgery versus FG technique is not adequately investigated yet but this was not the aim of this study.

The percutaneous technique that was applied in the majority of robot cases (38 patients) helps decrease blood loss because open dissection is minimized.[15]

The main limitation of the study is due to the lack of data about the radiation exposure due to pre-operative CT scan and the levels involved in fusion.

CONCLUSION

This meta-analysis demonstrates that the accuracy of pedicle screw placement with robotic technology is substantially greater than with FG. In fact, the robotic approach allows significantly lower complication rates, fewer cases of violation of the proximal articular facet, less intraoperative exposure to radiation, even if it requires longer surgical times than the FG technique. However, there are potential confounders in our meta-analysis due to lack of data such as cumulative radiation dose because of pre-operative CT-scan, patient comorbidities, surgeon's learning curve, concomitant surgical procedures, and the level of spinal fusion.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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