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ORIGINAL ARTICLE

Superior facet joint violation between open and minimally invasive techniques in lumbar fusion surgery: An updated systematic review and meta-analysis

Po-Chun Liu[a], Yi Lu[a], Hsi-Hsien Lin[a,b], Yu-Cheng Yao[a,b], Ming-Chau Chang[a,b], Shih-Tien Wang[a,b], Po-Hsin Chou[a,b,*]

[a]School of Medicine, National Yang Ming Chiao Tung University, Taipei, Taiwan, ROC; [b]Department of Orthopedics and Traumatology, Taipei Veterans General Hospital, Taipei, Taiwan, ROC

Abstract

Background: Superior facet joint violation (FJV) is a potential risk factor for adjacent segment disease following lumbar fusion surgery. We sought to conduct a systematic review and meta-analysis to compare screw-related superior FJV rates between the open and different minimally invasive (MI) techniques—fluoroscopy-based, 3D-image navigation, and navigation with robotic assistance—in adult lumbar fusion surgery.

Methods: We searched original articles comparing the rates of screw-related FJV between the open and different MI techniques in adult lumbar fusion surgery for lumbar degenerative diseases in PubMed, EMBASE, and the Cochrane Library from inception to September 2021. We compared the numbers of top-level pedicle screws and associated superior FJVs in the main analyses and performed subgroup analysis based on different MI techniques to examine whether individual MI approaches differed in superior FJV rate. Risk ratio (RR) and 95% confidence interval (CI) were calculated in a random-effect meta-analysis.

Results: Included in the meta-analysis were 16 articles with 2655 patients and 4638 top-level pedicle screws. The pooled analysis showed no significant difference in superior FJV rates between the MI and open groups (RR: 0.89, 95% CI: 0.62-1.28). The subgroup analysis demonstrated that the overall rates of superior FJV were 27.1% (411/1518) for fluoroscopy-based, 7.1% (43/603) for 3D-image navigation, and 3.2% (7/216) for navigation with robotic assistance. Compared with the open method, the overall RRs were 1.53 (95% CI: 1.19-1.96) for fluoroscopy-based, 0.41 (95% CI: 0.22-0.75) for 3D-image navigation, and 0.25 (95% CI: 0.08-0.72) for navigation with robotic assistance.

Conclusion: Among the three common MI techniques, fluoroscopy-based can be associated with a higher risk of superior FJV, while both 3D-image navigation and navigation with robotic assistance may be associated with lower risks as compared with the open method. Considering the limitations of the study, more trials are needed to prove these clinical findings.

Keywords: Minimally invasive surgical procedures; Pedicle screws; Spinal fusion; Systematic review; Zygapophyseal joint

1. INTRODUCTION

Lumbar fusion surgery with a pedicle screw-based system has been widely used in recent years to treat lumbar degenerative diseases.[1] Although this technique was traditionally conducted with an open method, the emergence of minimally invasive (MI) techniques has made percutaneous pedicle screws more popular because these techniques have reduced intraoperative blood loss, lessened postoperative pain, and allowed for faster recovery due to reduced soft tissue dissection.[2–4] The three fundamental methods of MI surgery for pedicle screw insertion are as follows: fluoroscopy-based; 3D-image navigation with 3D C-arm, O-arm, or computed tomography (CT) scan guidance; and navigation with robotic assistance.[5]

In vitro biomechanical studies have shown that injury to the facet joint may alter its load-bearing capability and original biomechanics[6] and subsequently accelerate degeneration of the joint.[7] Therefore, superior facet joint violation (FJV) has been regarded as one of the causes of adjacent segment degeneration (ASD) after lumbar fusion surgery[8,9] and reoperation at 2 years and 3 years postoperatively.[10]

Accordingly, the consensus is that maintaining integrity of superior facet joints is generally required to avoid ASD regardless of technique (MI or open), and several studies have highlighted the risk of superior FJV associated with different surgical techniques.[11–27] In a meta-analysis conducted in 2015, Wang et al found similar rates of superior FJV for MI and open methods (MI: 18.2%; open: 18.7%).[28] Innovative technologies and techniques have revolutionized MI spine surgery in the past decade.[29] However, no existing review articles have investigated the

* Address correspondence. Dr. Po-Hsin Chou, Department of Orthopedics and Traumatology, Taipei Veterans General Hospital, 201, Section 2, Shi-Pai Road, Taipei 112, Taiwan, ROC. E-mail address: choupohsin@gmail.com (P.-H. Chou).

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influence of the evolution and diversity of MI techniques when comparing them with the open approach in terms of superior FJV. Hence, the objective of this systematic review and meta-analysis was to compare the rates of superior FJV between the open method and the different MI techniques: fluoroscopy-based; 3D-image navigation with 3D C-arm, O-arm, CT scan guidance; and navigation with robotic assistance.

2. METHODS

2.1. Protocol and registration

This review study was designed following A MeaSurement Tool to Assess systematic Reviews 2 (AMSTAR 2)[30] and Preferred Reporting Items for Systematic review and Meta-Analysis Protocols (PRISMA-P).[31] The protocol is available at PROSPERO (https://www.crd.york.ac.uk/PROSPERO/),[32] registration number CRD42020212333. The writing of the present article was done according to PRISMA statements.[33]

2.2. Search strategy

Two authors independently searched PubMed, EMBASE, the Cochrane Library, Web of Science, and Clinicaltrial.gov. The search was performed on September 30, 2021, with no time-frame restrictions. Only English-language published original articles were retrieved. The search strategy adhered to the recommendations by Aromataris and Riitano.[34] The PICO elements were initially constructed (*population*: spondylolisthesis, spinal fusion; *intervention*: minimally invasive; *comparator*: open; *outcome*: facet joint violation). We extended the query to the associated Medical Subject Headings (MeSH). The MeSH terms included spondylolisthesis, spondylolysis, spondylosis, spinal fusion, arthrodesis, pedicle screws, bone screws, bone nails, minimally invasive surgical procedures, and zygapophyseal joint. Entries of MeSH terms in PubMed were finally added to the query. The Boolean operator "OR" was used to connect the components in each PICO element and "AND" was used to link the PICO elements. The detailed steps are provided in the Supplementary Data (http://links.lww.com/JCMA/A159).

2.3. Study selection

The eligibility criteria included (1) original clinical comparative studies, (2) studies comparing the rates of FJV between MI and open pedicle screw placement in lumbar fusion surgery for patients with lumbar degenerative diseases, (3) studies reporting the number of pedicle screws and FJVs in both groups, (4) studies describing in detail the surgical techniques in both groups, and (5) studies in which CT was used in defining FJV. Two authors independently screened the article titles and abstracts using Rayyan (https://rayyan.qcri.org/).[35] The full texts of articles which potentially met the eligibility criteria were independently reviewed by the two authors.

2.4. Quality assessment

Two authors independently evaluated the quality of the included studies with the modified Jadad score for randomized controlled trials[36] and the Newcastle-Ottawa Quality score Assessment Scale (NOS) (http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp) for comparative observational studies.

2.5. Data extraction

Two authors independently extracted the data. The outcomes of interest were the rates of FJV in MI and open pedicle screw placement. The following data were also extracted: (1) author names, (2) publication year, (3) study design, (4) operation period, (5) operation country, (6) surgical fusion levels, (7) surgical techniques, (8) distribution of age, gender, and body mass index (BMI) of patients, (9) FJV grading criteria, and (10) pathologies of patients. Top-level pedicle screws and associated superior FJVs were noted as described in the article. We categorized surgical techniques into fluoroscopy-based, 3D-image navigation, and navigation with robotic assistance. We defined 3D-image navigation as guidance with 3D C-arm, O-arm, or CT scan for screw insertion.

2.6. Statistical analysis

FJV was treated as a binary variable. FJV grades other than grade 0 were considered "yes" if FJV was classified into more than two grades in the study. We focused on top-level pedicle screws and associated superior FJVs in the main analyses. Analyses including all identified pedicle screws and FJVs are provided in the Supplementary Data (http://links.lww.com/JCMA/A159). Risk ratio (RR) and 95% confidence interval (CI) were calculated and RR < 1 indicated a protective effect against FJV of the MI approach. A random effects model with DerSimonian-Laird estimator was used to estimate the overall RR to account for inconsistency between the individual studies.[37] The point estimate of heterogeneity magnitude, the τ^2 statistic, was reported.[38] We assessed the proportion of total variability attributed to heterogeneity with the I^2 statistic. $I^2 > 50\%$ and $>75\%$ were considered to represent moderate and high heterogeneity, respectively.[39]

To examine whether improvements in the MI approach reduced the FJV rate, subgroup analysis was performed based on the MI technique adopted in the study: fluoroscopy-based, 3D-image navigation, or navigation with robotic assistance. If two MI techniques were adopted in a single study, the two groups of patients were separately compared with the open group in each subgroup analysis. If the study used a multigrade classification, sensitivity analysis was performed based on the different definitions of FJV. Publication bias was graphically evaluated using funnel plots and the trim-and-fill method was applied if publication bias existed. All tests were two-tailed, and $p < 0.05$ was considered significantly different. All statistical analyses and plot drawing were performed with the "metaphor" package[40] in the R environment (www.R-project.org/).[41]

3. RESULTS

3.1. Literature search

Fig. 1 shows the detailed selection process. We initially found 247 nonduplicate articles. After screening the titles and abstracts, 17 remained.[11–27] Of these 17 articles, one was excluded due to a lack of description of the exact number of FJV cases.[11] Among the 16 eligible studies, 13 reported superior FJVs in the text. A sample size of 2655 patients and 6389 pedicle screws (4638 top-level pedicle screws in 2323 patients) were included in the overall meta-analysis.

3.2. Characteristics of selected studies

Table 1 shows the selected characteristics of the 16 included studies. All extracted data are described in the Supplementary Data (http://links.lww.com/JCMA/A159). Only one study was a randomized control trial.[17] All studies used CT to assess FJV, while Archavlis et al additionally used the C-OnSite technique. Three studies adopted two types of MI techniques.[14,18,19] Seven studies enrolled only patients undergoing one-level lumbar fusion surgery.[13,18,19,23,25–27] Yson et al did not describe the demographic data of patients.[15] Multiple FJV grading criteria were used. Six studies used the method described by Babu et al,[12,16,19,21,23,26] four studies used Seo's classification,[15,18,22,24] and the remaining six studies

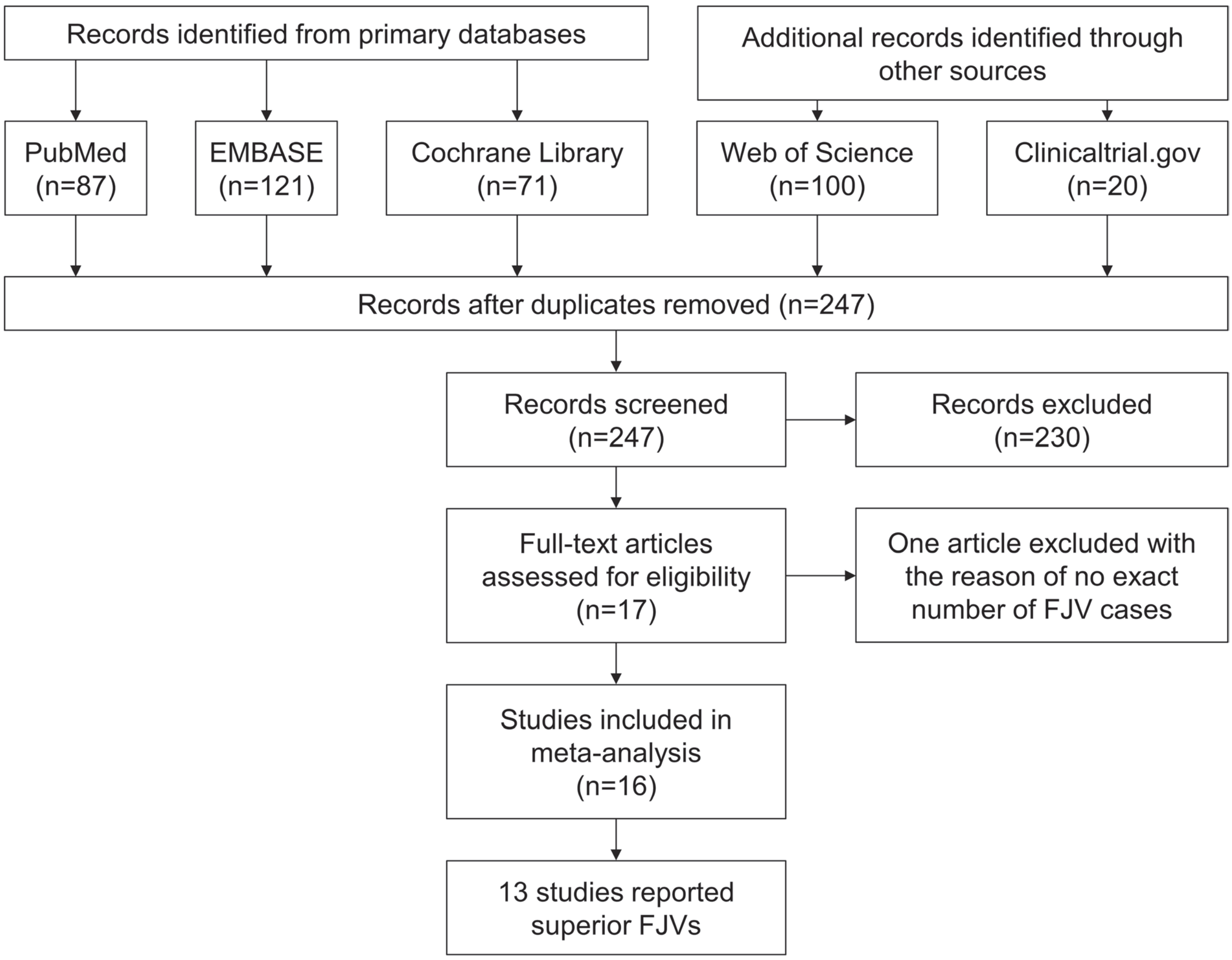

Fig. 1 Flow diagram of study search and selection. FJV = facet joint violation.

treated FJV as a binary variable.[13,14,17,20,25,27] The earliest four studies were included in the previous review by Wang et al.[12–15,28]

3.3. Quality assessment

The overall quality of the 15 comparative observational studies was good (Supplementary Data, http://links.lww.com/JCMA/A159). The NOS score ranged from 6 to 9, of a maximum of 9 points. Eleven studies lost one to two stars due to a lack of description of how they controlled for confounders.[13–16,18,19,21–24,26] Five studies further lost one star because they did not mention how many patients meeting the inclusion criteria received postoperative CT scan[12,13,23,25,26] and the study by Wu et al lost one star since more than 15% of subjects were lost to follow-up. The one randomized controlled trial got 6.5 out of 8 points using the modified Jadad score because it was single-blinded.[17]

3.4. Meta-analysis

The overall rates of superior FJV were 19.7% (461/2337) and 19.6% (451/2,301) in the MI and open groups, respectively. The pooled analysis showed that there was no significant difference in superior FJV rates between the two groups (RR: 0.89, 95% CI: 0.62-1.28) using the random effects model (Fig. 2). However, significant heterogeneity was found with I^2 = 85.5% (p < 0.001). Among 13 studies reporting superior FJVs, five described an increased FJV risk associated with the MI surgery (Fig. 2), and all five studies adopted the fluoroscopy-based technique in the MI group (Table 1). In contrast, among four studies showing a reduced risk of superior FJV associated with the MI surgery, none adopted the fluoroscopy-based technique in the MI group (Table 1). The analyses incorporating the fixed effects model and all 16 studies showed similar results (Supplementary Data, http://links.lww.com/JCMA/A159).

3.5. Subgroup analysis

Because of the significant statistical heterogeneity and the diverse MI techniques used in the studies, subgroup analysis was performed. Among 13 studies reporting superior FJV, nine adopted fluoroscopy-based techniques in the MI group, five adopted 3D-image navigation, and two adopted navigation with robotic assistance (Fig. 3). Lau et al, Wu et al, and Archavlis et al adopted two kinds of techniques in the MI group.[14,18,19] The overall rates of superior FJV were 27.1% (411/1,518) for fluoroscopy-based, 7.1% (43/603) for 3D-image navigation, and 3.2% (7/216) for robotic assistance.

The pooled RR of superior FJV for the fluoroscopy-based MI technique was 1.53 (95% CI: 1.19-1.96). Only one of nine studies reported a nonsignificantly reduced risk in the MI group, in which two surgeons performed different numbers of MI and open surgeries and the patients in the open group had higher BMI.[14] The pooled RR of superior FJV for the 3D-image navigation technique was 0.41 (95% CI: 0.22-0.75). Lau et al used O-arm navigation and Huang et al used C-arm navigation rather than CT navigation adopted by the other three studies.[14,25] The

Table 1

Selected Characteristics of the Included Studies.

Study	Operation period	Surgical technique in MI group	Surgical technique in open group
Babu et al[12]	2007-2011	Fluoroscopy	NA
Jones-Quaidoo et al[13]	NA	Fluoroscopy	Freehand
Lau et al[14]	2006-2011	Group 1: O-arm navigation; Group 2: Fluoroscopy	Fluoroscopy
Yson et al[15]	2006-2011	CT navigation	CT navigation
Tian et al[16]	2013-2014	CT navigation	CT navigation
Hyun et al[17]	2013-2015	Robotic assistance	Fluoroscopy
Wu et al[18]	2010-2012	Group1: Fluoroscopy; Group 2: CT navigation	Freehand
Archavlis et al[19]	2012-2016[a]	Group1: Robotic assistance; Group 2: Fluoroscopy	Fluoroscopy
Teles et al[20]	2009-2016	Fluoroscopy	Fluoroscopy
Zhang et al[21]	2016-2018	Robotic assistance	Fluoroscopy
Murata et al[22]	2014-2017	Fluoroscopy (coaxial view)	Fluoroscopy (lateralview)
Patel et al[23]	2014-2018	Fluoroscopy	Freehand
To et al[24]	2016-2017	Fluoroscopy	Freehand[b]
Huang et al[25]	2016-2019	C-arm navigation	Fluoroscopy
Maharjan et al[26]	2013-2016	Fluoroscopy	Fluoroscopy
Mimura et al[27]	2001-2014	Fluoroscopy	NA
Study	**FJV evaluated by**	**FJV assessing Instrument**	**FJV Grading Criteria**
Babu et al[12]	Two observers	CT	Babu's method
Jones-Quaidoo et al[13]	Three spine surgeons	CT	Intra- vs extra- articular
Lau et al[14]	NA	CT	Intra- vs extra- articular
Yson et al[15]	A spine surgeon, a spine research fellow, an orthopedic resident	CT	Seo's method
Tian et al[16]	Three observers	CT	Babu's method
Hyun et al[17]	A spine surgeon	CT	No description
Wu et al[18]	Two surgeons	CT	Seo's method
Archavlis et al[19]	A spine surgeon	CT/C-OnSite	Babu's method
Teles et al[20]	Two observers	CT	Intra- vs extra- articular
Zhang et al[21]	A spine surgeon, a radiologist	CT	Babu's method
Murata et al[22]	Two observers	CT	Seo's method
Patel et al[23]	Two observers	CT	Babu's method
To et al[24]	Three observers	CT	Seo's method
Huang et al[25]	A spine surgeon	CT	Intra- vs extra- articular
Maharjan et al[26]	NA	CT	Babu's method
Mimura et al[27]	NA	CT	Intra- vs extra- articular
Study	**FJV % in MI group (no. of FJV/pedicle screws)**	**FJV % in open group (no. of FJV/pedicle screws)**	**Appraise[c]**
Babu et al[12]	40.2 (123/306) (top)	34.1 (86/252) (top)	8/9
Jones-Quaidoo et al[13]	13.6 (36/264) (all); 12.9 (17/132) (top)	6.1 (16/263) (all); 5.3 (7/131) (top)	7/9
Lau et al[14]	O-arm: 5.4 (4/74) (top); Fluoroscopy: 2.4 (5/210) (top)	4.3 (12/280) (top)	8/9
Yson et al[15]	4.0 (4/125) (top)	26.5 (65/245) (top)	7/9
Tian et al[16]	3.7 (5/136) (top)	14.9 (22/148) (top)	7/9
Hyun et al[17]	0.0 (0/130) (all)	0.7 (1/140) (all)	6.5/8
Wu et al[18]	Fluoroscopy: 28.3 (13/46) (top); CT: 10.4 (5/48) (top)	15.4 (16/104) (top)	7/9
Archavlis et al[19]	Robot: 2.6 (3/116) (top); Fluoroscopy: 21.9 (28/128) (top)	5.6 (8/144) (top)	7/9
Teles et al[20]	21.9 (21/96) (top)	7.2 (12/166) (top)	9/9
Zhang et al[21]	4.0 (4/100) (top)	26.0 (26/100) (top)	7/9
Murata et al[22]	0.5 (2/394) (all)	1.8 (8/445) (all)	7/9
Patel et al[23]	41.3 (99/240) (top)	30.5 (64/210) (top)	6/9
To et al[24]	4.5 (8/176) (all)	10.4 (21/202) (all)	7/9
Huang et al[25]	10.9 (24/220) (top)	25.3 (57/225) (top)	8/9
Maharjan et al[26]	38.4 (86/224) (top)	28.9 (67/232) (top)	7/9
Mimura et al[27]	14.0 (19/136) (top)	14.1 (9/64) (top)	9/9

[a]Robotic assistance: 2015-2016; fluoroscopy: 2013-2014; open: 2010-2012.
[b]Fluoroscopy if needed.
[c]The Newcastle-Ottawa Quality score Assessment Scale (nine points) is applied to observational studies; the modified Jadad score is applied to randomized controlled trials (eight points).
CT = computed tomography; FJV = facet joint violation; MI = minimally invasive.

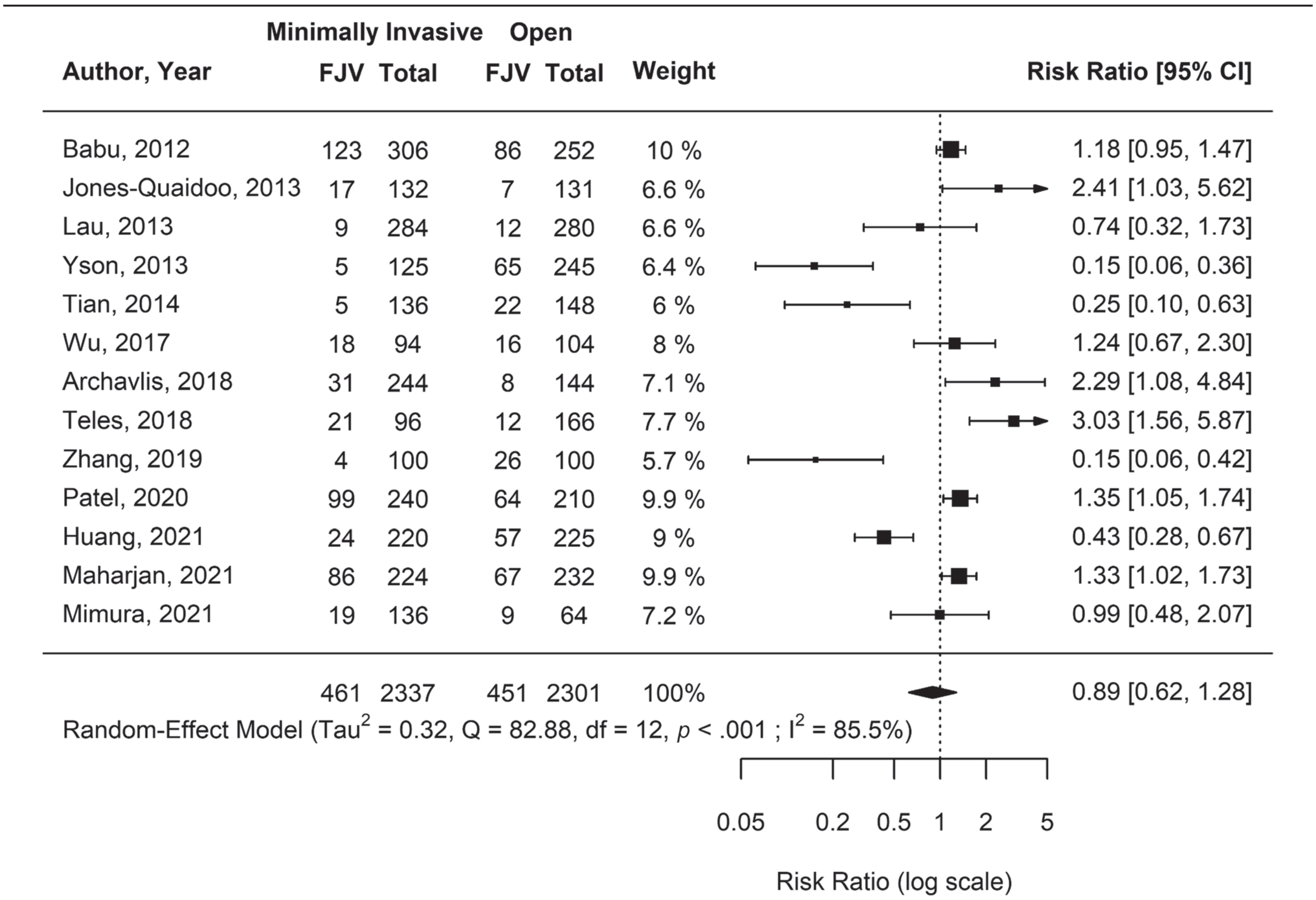

Fig. 2 Forest plot of all studies with their respective RRs and 95% CIs, numbers of pedicle screws and superior FJVs, and overall RR and statistics of heterogeneity. CI = confidence interval; FJV = facet joint violation; RR = risk ratio.

sensitivity analysis removing the studies by Lau et al and Huang et al resulted in a reduced RR (0.29, 95% CI: 0.12-0.69) of superior FJV. Analysis of the two studies using robotic assistance in the MI group showed that the overall RR of superior FJV was 0.25 (95% CI: 0.08-0.72) for the MI surgery. The analyses incorporating the fixed effects model and all 16 studies showed similar results (Supplementary Data, http://links.lww.com/JCMA/A159).

3.6. Sensitivity analysis

Grade I FJV in Babu's classification was defined as "screw in lateral facet but not in facet articulation,"[12] which may not be considered an actual FJV event. We therefore performed sensitivity analysis by alternatively defining only Babu's Grades II and III as FJV. Fewer FJV events were observed, resulting in the larger CIs of the estimated RRs (Supplementary Data, http://links.lww.com/JCMA/A159). The overall RR changed from 1.53 to 1.81 (95% CI: 1.36-2.40) for fluoroscopy-based, from 0.41 to 0.39 (95% CI: 0.19-0.82) for 3D-image navigation, and from 0.25 to 0.29 (95% CI: 0.08-1.08) for navigation with robotic assistance.

3.7. Publication bias

The funnel plots depicted a symmetrical distribution of log RRs of the 13 studies reporting superior FJV, suggesting a low possibility of publication bias (Fig. 4). Only one pseudo-filled study was suggested in the trim-and-fill analysis among the studies adopting 3D-image navigation, resulting in a reduced RR of superior FJV from 0.41 to 0.33 (95% CI: 0.17-0.64). The funnel plots incorporating all 16 studies, provided in the Supplementary Data (http://links.lww.com/JCMA/A159), show an absence of small negative studies, with the trim-and-fill analysis suggesting four pseudo-filled studies.

4. DISCUSSION

Based on our results, the overall rates of superior FJV were 19.7% (461/2337) and 19.6% (451/2301) in the MI and open groups, respectively. The pooled analysis using the random effects model showed no significant difference in superior FJV rates between the two groups (RR: 0.89, 95% CI: 0.62-1.28). However, significant heterogeneity was found with I^2 = 85.5% (p < 0.001). Compared with the open approach, the RR was 1.53 (95% CI: 1.19-1.96) for fluoroscopy-based, 0.41 (95% CI: 0.22-0.75) for 3D-image navigation, and 0.25 (95% CI: 0.08-0.72) for navigation with robotic assistance.

ASD is not uncommon following lumbar fusion surgery, with the pooled incidences of 12.1% (95% CI: 8.2-16.0%) and 3.2% (95% CI: 2.5-4.0%) reported at 2-5 and 5-10 years postoperatively.[42] Although the etiologies for ASD are multifactorial and elusive, several patient- and surgical-related risk factors for ASD have been noted.[43,44] Among these is superior FJV during pedicle screw insertion.[45] Superior FJV may alter the load-bearing capability of the motion segment in vitro and ultimately lead to the occurrence of ASD clinically.[7] Moreover, Levin et al reported that superior FJV was independently associated with a higher reoperation rate at 2 years (15.2%) and 3 years (19.6%)

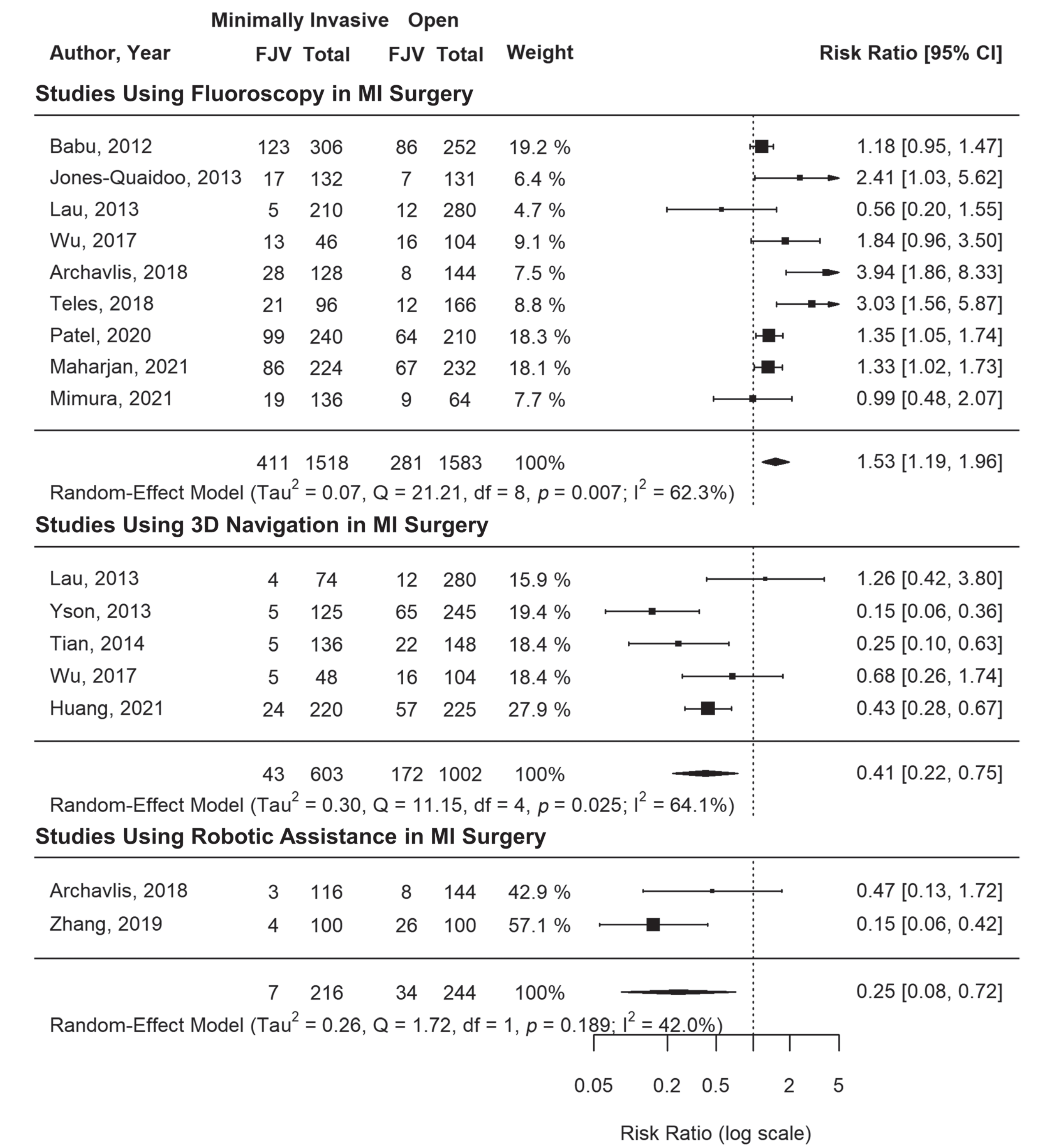

Fig. 3 Forest plot of subgroup analysis by different minimally invasive techniques with their respective RRs and 95% CIs, number of pedicle screws and superior FJVs, and overall RR and statistics of heterogeneity. CI = confidence interval; FJV = facet joint violation; MI = minimally invasive; RR = risk ratio.

postoperatively, as well as diminished improvement in quality of life.[10] During lumbar fusion surgery, surgeons should avoid superior FJV to avoid ASD and improve the subsequent long-term quality of life of patients.

Among the clinical papers included for meta-analysis, different criteria for accessing superior FJV were adopted, such as Babu's and Seo's classifications. The different classifications for FJV may have contributed to the heterogeneity in the statistical results. Babu's classification is widely accepted and can enable spine surgeons to easily distinguish between different gradings in the axial view of the CT scan.[12] However, Grade I FJV in Babu's classification, defined as "screw in lateral facet but not in facet articulation," may not be an actual FJV event. Accordingly, we conducted sensitivity analysis by defining only Grades II and III as FJV and observed similar results.

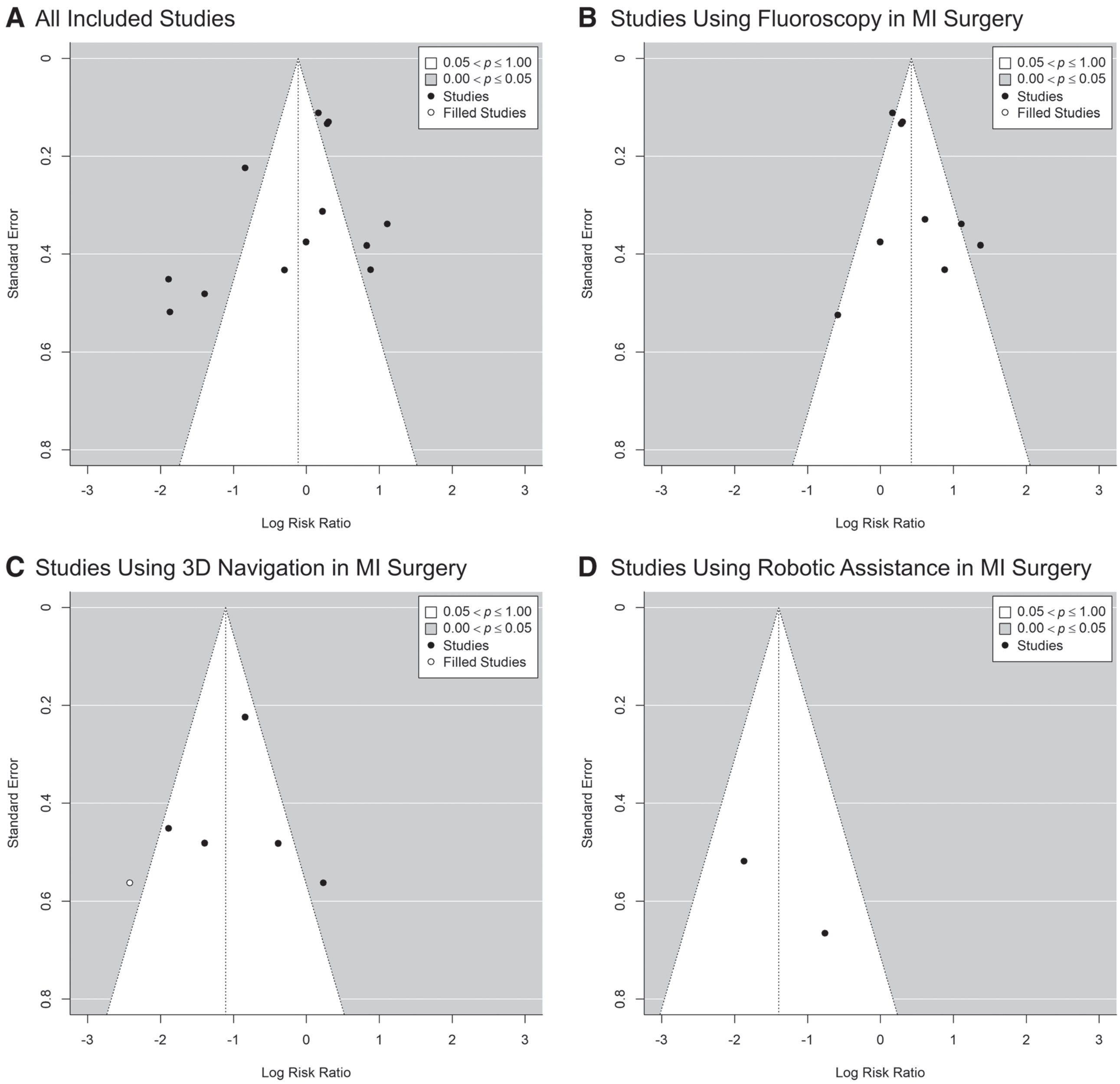

Fig. 4 Funnel plots of all studies and subgroup analysis showing an approximately symmetrical distribution of the studies. MI = minimally invasive.

Wang et al reported similar superior FJV rates between MI and open lumbar fusion surgeries in cases recruited from 2006 to 2011.[28] However, innovative technologies and techniques have revolutionized MI spine surgery within the past decade. In the clinical setting of MI surgery, three possible methods are used for pedicle screw insertion in lumbar fusion surgery: fluoroscopy-based; 3D-image navigation with 3D C-arm, O-arm, or CT scan guidance; and navigation with robotic assistance, based on different surgeons' preferences or the methods in use at the medical facility. The introduction of navigation has greatly affected spine surgery and will continue to make surgeries safer and more efficient.[29]

In our meta-analysis, navigation with robotic assistance best avoided superior FJV as compared with the open approach. In the clinical setting, surgeons use a T-shaped handle with navigation sensors guided by intraoperative real-time 3D images and use a drill to make the initial trajectory, then place the guide wires for percutaneous pedicle screw insertion regardless of the type of 3D-image navigation used. However, surgeons still need to hold the T-shaped handle tightly without any movement to create the optimal entrance point and screw trajectory. Soft tissue must be traversed to place the guided wires and screws, and any tiny movement at the skin layer can create great bias at the docking site. However, in the use of navigation with robotic assistance, robotic arms will follow the direction and trajectory of the surgeons' design based on real-time intraoperative 3D images and help to avoid the errors of manual control at the skin layer and the subsequent huge bias at the docking site. Obese patients have a thicker subcutaneous fat layer and may potentially have a greater risk for superior FJV in the MI surgery with fluoroscopy or 3D-image navigation, as reported by Lau et al.[14] However, the much greater cost of navigation with robotic assistance is a significant obstacle to its greater use.[29,46]

The possible risk factors associated with superior FJV are more depth of the spine,[12,23] higher BMI,[14,23,26] more caudal lumbar level from L2 to L5,[15,16] greater facet angle,[20,23] and larger pedicle screw angle.[25] More tissue needs to be traversed to place the guided wires and percutaneous screw in patients with obesity, high BMI, or a thick layer of subcutaneous fat. Any movement at the skin layer will increase the displacement of the entry point and subsequently lead to an incorrect trajectory.

Different lumbar levels have unique anatomic characteristics with different facet joint angles and transverse intertangential angles,[47] adding to the complexity of the operation. Surgeons must take into account these potential risk factors to avoid superior FJV.

Several limitations existed in the study. Although we performed subgroup analysis by different MI methods to account for the influence of the diverse techniques, moderate heterogeneity still presents. First, the classifications of FJV were heterogeneous and might therefore have introduced some bias. Second, different spine surgery teams in different countries may employ different clinical techniques, which could potentially bias the results. Different races, indications, and demographic characteristics among the patient populations in the included studies could also have contributed to the statistical heterogeneity. The control of the comparison was the pedicle screw insertion in the open method with freehand,[13,18,23,24] fluoroscopy-based,[14,17,19–22,25,26] or CT scan navigation.[15,16] The comparator was not consistent and could also be an origin of the statistical heterogeneity. Moreover, the present study includes only two articles reporting limited subjects undergoing navigation with robotic assistance, and more studies are needed to draw a reliable conclusion. Finally, the fact that this is a pure radiology-based analysis without further analyzing patients' reported outcomes and related ASD was another weakness.

In conclusion, superior FJV is not uncommon following pedicle screw insertion in the treatment of degenerative lumbar diseases. The three common MI techniques for pedicle screw insertion had different RRs of superior FJV as compared with the open method. Fluoroscopy-based techniques can be associated with a higher risk of superior FJV, while both 3D-image navigation and navigation with robotic assistance may be associated with lower risks. Considering the limited sample size and other limitations of the study, more large-scale prospective randomized controlled trials are needed to prove these clinical findings.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data related to this article can be found at http://links.lww.com/JCMA/A159.

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