Systematic Review and Meta-Analysis

Medicine®

OPEN

Comparison of accuracy and safety between robot-assisted and conventional fluoroscope assisted placement of pedicle screws in thoracolumbar spine

A meta-analysis

Chuntao Li, MD[a], Wenyi Li, MD[b,*], Shangju Gao, MD[b], Can Cao, MD[b], Changren Li, MD[c], Liang He, MD[c], Xu Ma, MD[c], Meng Li, MD[d]

Abstract

Objective: The purpose of this systematic review and meta-analysis is to explore the screw positioning accuracy, complications related to pedicle screw implantation, revision rate and radiation exposure between robot screw placement and traditional fluoroscopic screw placement.

Methods: We searched several databases, including CNKI, Wanfang database, cqvip datebase, PubMed, Cochrane library and EMBASE, to identify articles that might meet the criteria. Meta-analysis was performed using Revman 5.3 software.

Results: A total of 13 randomized controlled trial were included. The results showed that the pedicle screw accuracy of the robot assisted group was significantly better than that of the conventional freehand (FH) group (OR=3.5, 95% confidence interval [CI] [2.75,4.45], $P<.0001$). There was no significant difference in the complications caused by pedicle screw implantation between the robot-assisted group and the conventional FH group [OR=0.39, 95%CI (0.10,1.48), $P=.17$]. The rate of facet joint invasion in the robot-assisted group was significantly lower than that in the conventional FH group (OR=0.06, 95%CI [0.01,0.29], $P=.0006$). The revision rate in the robot-assisted group was significantly lower than that in the conventional FH group (OR=0.19, 95%CI [0.05,0.71], P=0.0.01). There was no significant difference in the average radiation of pedicle screws implantation between the robot-assisted group and the conventional FH (mean difference=-7.94, 95%CI [-20.18,4.30], $P=.20$).

Conclusion: The robot-assisted group was significantly better than the conventional FH in the accuracy of pedicle screw placement and facet joint invasion rate and revision rate. There was no significant difference in the complication and fluoroscopy time between the two groups.

Abbreviations: CI = confidence interval, FH = freehand.

Keywords: fluoroscopy, meta-analysis, pedicle screws, placement of pedicle screws, robot-assisted

1. Introduction

Pedicle screw fixation is a common method to restore spinal stability. The pedicle of thoracic vertebra is small, the average diameter is about 8 mm, and there are many important nerves and blood vessels adjacent to the pedicle. The failure of screw placement often leads to serious complications. At present, the technique of freehand pedicle screws placement under fluoroscopy guidance is most commonly used in clinic. However, the accuracy of pedicle screws placement under fluoroscopy is affected in many aspects, the lack of experience of the operator or the morphological variation of pedicle may lead to the failure of pedicle screws placement.[1] With the development of orthopaedical robot technology, spinal internal fixation technology ushered in a new way. However, some scholars hold a different point of view, they believe that the current evidence cannot prove that robot-assisted are more accurate than conventional fluoroscope assisted placement of pedicle screws.[2,3] The lateral slip of the casing at the entrance and even the software used by the robot are all possible reasons for the decrease in the accuracy of robot-assisted placement of pedicle screws.[3,4] Some scholars support that robot-assisted placement of pedicle screws can achieve higher accuracy.[5] These published meta analyses have some

Editor: Hyeun Sung Kim.

The authors have no funding and conflicts of interest to disclose.

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

[a] Hebei North University, Zhangjiakou, Hebei, China, [b] Department of Orthopedics, Hebei General Hospital, Shijiazhuang, Hebei, China, [c] Hebei North University, Zhangjiakou, Hebei, China, [d] Hebei Medical University, Shijiazhuang, Hebei, China.

[*] Correspondence: Wenyi Li, Department of Orthopedics, Hebei General Hospital, Shijiazhuang, Hebei, China (e-mail: liwenyi71@163.com).

How to cite this article: Li C, Li W, Gao S, Cao C, Li C, He L, Ma X, Li M. Comparison of accuracy and safety between robot-assisted and conventional fluoroscope assisted placement of pedicle screws in thoracolumbar spine: a meta-analysis. Medicine 2021;100:38(e27282).

Received: 21 January 2021 / Received in final form: 12 August 2021 / Accepted: 1 September 2021

http://dx.doi.org/10.1097/MD.0000000000027282

limitations, such as the number of pedicle screw placement is still small,[6] or the included studies are non-randomized controlled trials.[5,7] Therefore we conduct a meta-analysis to systematically evaluate the accuracy and safety of robot navigation and traditional fluoroscope assisted placement of pedicle screws.

2. Materials and methods

Randomized controlled trials of pedicle screw implantation guided by robot-assisted and fluoroscopy was searched in CNKI, Wanfang database, PubMed, Cochrane collaboration network, Web of science, EMbase and CBM database from the establishment of the database to December 2020. The search words include: robot, robotic, robotic-assisted, pedicle screw, freehand technique.

2.1. Inclusion and exclusion criteria

The inclusion criteria were established as follows: patients with lumbar degenerative diseases; this study must be a randomized controlled trial comparing robot-assisted pedicle screws placement with fluoroscopic guideline placement; at least one outcome must be included. The exclusion criteria are established as follows: Repeat publication; Unable to get full text; The result report is incomplete;

2.2. Statistical analysis

Meta-analysis was performed with Revman 5.3 software. The continuous outcomes are presented as mean difference and 95% confidence interval (CI), and odds ratio (OR) and 95% CIs are presented for counting outcomes. Chi-square test and I^2 were used to evaluate the heterogeneity. When $P > .1$ and $I^2 \leq 50\%$, the heterogeneity was small, and the fixed effect model was selected. If $P < .1$ and $I^2 > 50\%$ indicate greater heterogeneity, the subgroup analysis is carried out according to different conditions, and the random effect model is selected. Publication bias was evaluated by funnel plots.

2.3. Ethics approval statement

This study does not need to be approved by moral and ethical clerks.

3. Results

3.1. Search results

A total of 351 studies were retrieved in all databases. After removing repetition and screening, the articles that did not conform to the inclusion criteria were removed, and the final number of articles included was 13 (Fig. 1)

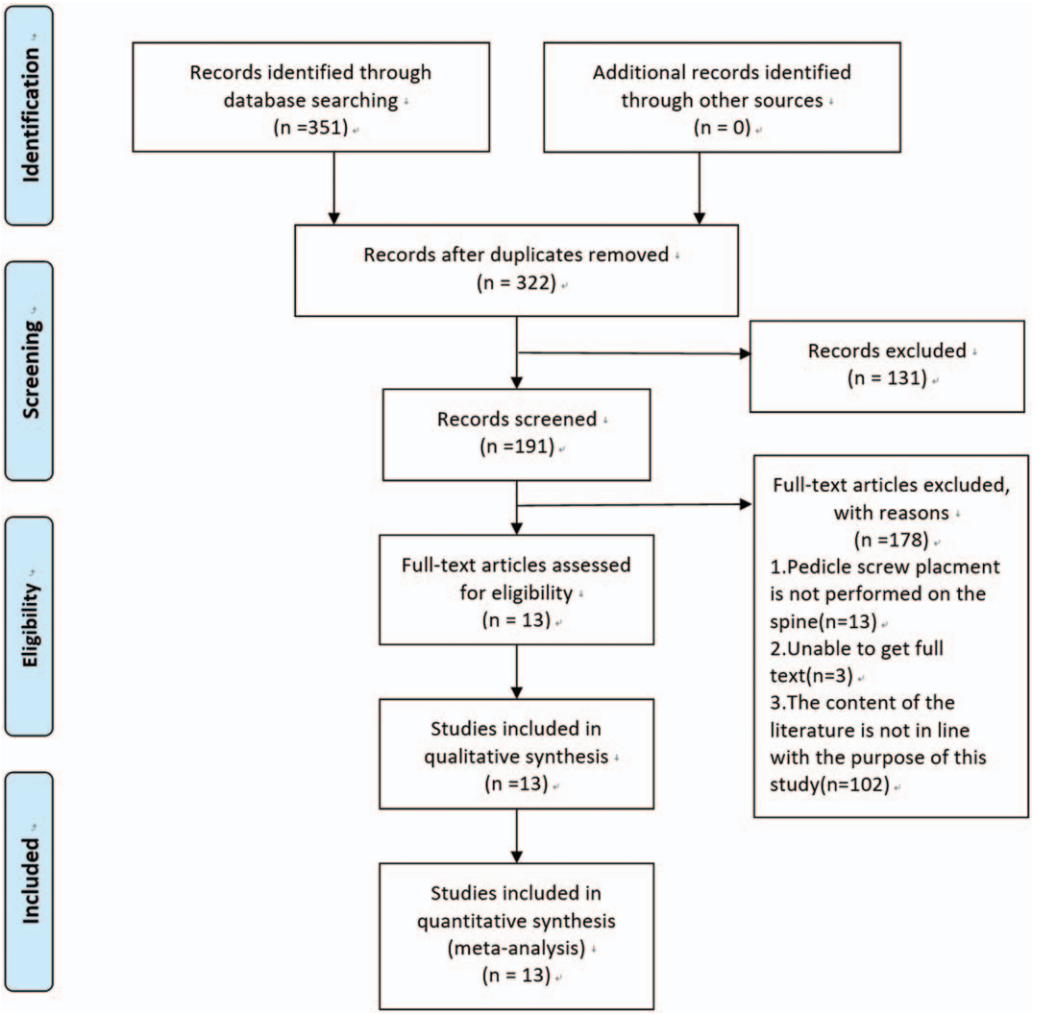

Figure 1. The flow chart of the literature screening process.

Table 1

Baseline characteristics of included studies.

Author	Year	Country	Robot type	Disease	Number of robot-assisted pedicle screws	Number of pedicle screws under fluoroscopy	Outcome
ZHAI[11]	2019	China	Mazor	Lumbar degenerative disease	276	255	①②
Yang[13]	2019	China	TiRobot	Lumbar degenerative disease	208	202	①
Xu[14]	2018	China	TiRobot	Lumbar degenerative disease	132	106	①②
Tian[15]	2016	China	TiRobot	Lumbar degenerative disease	102	88	①②
Huang[8]	2020	China	TiRobot	Lumbar degenerative disease	112	128	①②
Ringel[3]	2013	Germany	Mazor	Lumbar degenerative disease	146	152	①②④
Li [9]	2020	China	Mazor	Lumbar degenerative disease	32	50	①②⑤
Kim[18]	2017	South Korea	Mazor	Lumbar degenerative disease	156	172	①②③④
Hyun[17]	2017	South Korea	Mazor	Lumbar degenerative disease	130	140	①②③④⑤
Han[12]	2019	China	Mazor	Lumbar degenerative disease	532	584	①②③④
Feng[10]	2019	China	TiRobot	Lumbar degenerative disease	202	225	①④
Roser[16]	2013	Germany	Mazor	Lumbar degenerative disease	40	72	①⑤
Jamshidi[19]	2020	America	Mazor	Lumbar degenerative disease	374	111	⑤

①Accuracy of pedicle screw placement (pedicle screw is completely located in the cortex); ②Complications caused by pedicle screw implantation; ③Facet joint invasion rate; ④Revision rate. ⑤Fluoroscopy time (per pedicle screw).

3.2. General characteristics and risk of bias of the included study

The characteristics of the inclusion trial are shown in Table 1 Eight of the studies[8–15] were from China, two[3,16] from Germany, two[17,18] from South Korea and one[19] from the United States. Risk of bias of the included study is shown in Figure 2 and Figure 3.

4. Results of meta-analysis

4.1. Accuracy of pedicle screw placement (pedicle screw is completely located in the cortex)

A total of 12 articles[2–13] reported the accuracy of pedicle screw placement. The heterogeneity test was carried out on all the included literatures, and the results showed that there was heterogeneity among the studies ($I^2=76\%$), so the random effect model was used to merge. The results of meta-analysis showed that the accuracy of pedicle screw placement under robot-assisted was higher than that of traditional fluoroscopy guidance (OR = 2.91, 95%CI [1.77,4.80], $P<.0001$) (Fig. 4).

4.2. Complications caused by pedicle screw implantation

A total of 9 articles reported the complications associated with pedicle screw placement. The heterogeneity of all the included literatures was tested, and the results showed that the heterogeneity between the studies was small ($I^2=0\%$), so the fixed effect model was used to merge. The results of meta-analysis showed that there was no significant difference in complications between robot-assisted pedicle screw placement and traditional fluoroscopy. (OR = 0.39, 95%CI [0.10, 1.48], pendant 0.17) (Fig. 5).

4.3. Facet joint invasion rate

A total of 3 articles reported the rate of facet joint invasion. The heterogeneity of all the included literatures was tested, and the results showed that the heterogeneity between the studies was small ($I^2=0\%$), so the fixed effect model was used to merge. The results of meta-analysis showed that the invasion rate of pedicle screw implantation assisted by robot on facet joint was lower than that of traditional fluoroscopy. (OR = 0.06, 95%CI [0.01], 0.0006) (Fig. 6).

4.4. Revision rate

A total of 5 articles reported the revision rate. The heterogeneity of all the included literatures was tested, and the results showed that the heterogeneity between the studies was small ($I^2=0\%$), so the fixed effect model was used to merge. The results of meta-analysis showed that the revision rate of pedicle screws assisted by robot was lower than that of traditional fluoroscopy. (OR = 0.19, 95%CI [0. 05, 0. 71], Paddy. 0. 01) (Fig. 7).

4.5. Fluoroscopy time (per pedicle screw)

A total of 2 articles reported the fluoroscopy time of each pedicle screw. The heterogeneity of all the included literatures was tested, and the results showed that the heterogeneity among the studies was large (I2–99%), so the random effect model was used to merge. The results of Meta-analysis showed that there was no significant difference in fluoroscopy time of each pedicle screw between robot-assisted and traditional fluoroscopy. (mean difference = -7.94, 95%CI [- 20.18pr. 4.30], Play0.20) (Fig. 8).

4.6. Publication bias

The accuracy of pedicle screw placement was used to make inverted funnel chart for publication bias analysis. The results showed that the funnel chart was basically symmetrical, suggesting that there was no publication bias (Fig. 9).

5. Discussion

Pedicle screw is the most commonly used internal fixation in spinal surgery.[20] The lumbar pedicle is larger and more suitable for pedicle screw implantation. The pedicle of thoracic vertebrae is small, and pedicle screw placement under fluoroscopy is easy to fail.[21] Based on the three-column theory of the spine, pedicle screws can stabilize the three-column structure of the spine at the same time.[22] At present, fluoroscopy-guided pedicle screw placement is the most widely used technique in clinic. However,

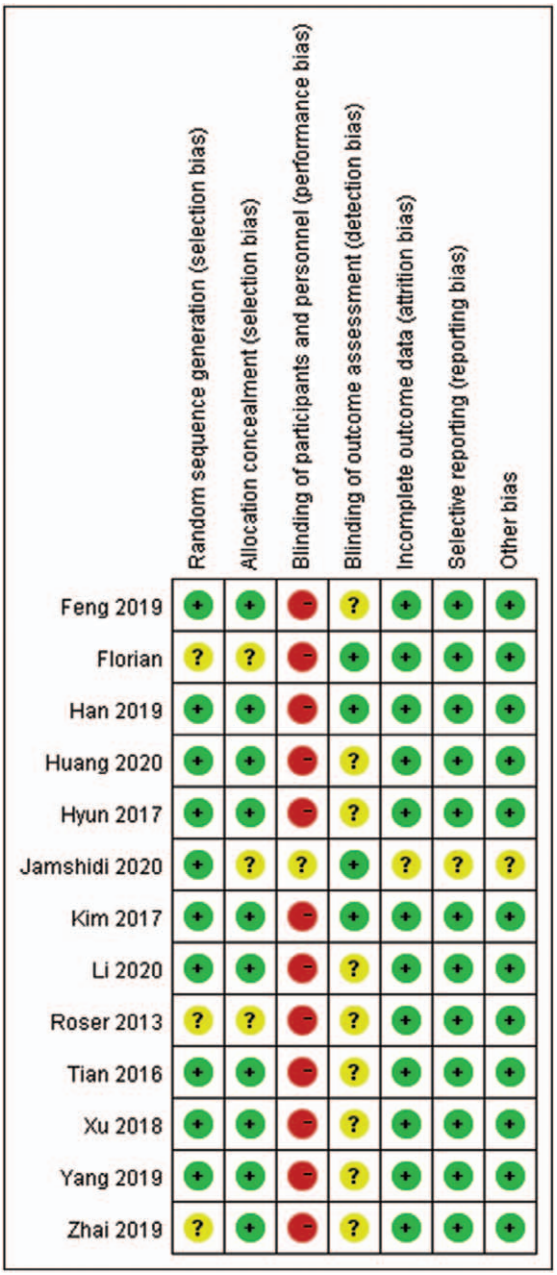

Figure 2. Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all included studies.

the variation of anatomical morphology of pedicle is often seen in clinic.[23] In addition, the unclear anatomical signs and the operator's lack of experience may lead to the failure of nail placement.

Under the available evidence, the incidence of misplacement of pedicle screws is in the range of 3% to 55%.[24] Even if senior physicians perform pedicle screw implantation, there is a screw adjustment rate of about 10%.[25] Among the various navigation technologies currently carried out, robot-assisted pedicle screw placement has attracted a lot of attention from spinal surgeons.[26] The robot has significant advantages in fine movement, reducing operator fatigue or physiological tremor, reducing radiation exposure, shortening pedicle screw placement time and so on. At present, the Israeli SpineAssist/Renaissance system is widely used in clinic.[27] SpineAssist / Renaissance system applies "Hover-T " technology. During the operation, the Hover-T frame was fixed on the spinous process of the patient, and then the fluoroscopy was carried out during the operation, and the images obtained were compared with the CT of the patients before operation, so as to complete the registration of each vertebral body.[28] Finally, the position of pedicle screw was designed, and then the operation of pedicle screw placement was completed. Because the bridge track is fixed to the spinous process of the patient's spine, the Renaissance system reduces the risk of misplacement of pedicle screws due to respiratory movement. The advantage of Chinese TIROBOT is that real-time navigation can be obtained according to the three-dimensional images during the operation.[29] However, some scholars have pointed out that in the process of 3D image reconstruction and registration, distortion will occur due to electromagnetic field deflection, which will affect the system error of the robot.[30] The accuracy of pedicle screw placement assisted by robot is more than 90%.[2,31–36] However, the existing meta analysis of robot-assisted pedicle screw placement is not rigorous, and different evaluation criteria of screw placement accuracy are often mixed and unified, and there is some controversy about the accuracy of robot-assisted screw placement. The meta-analysis of Liu et al[37] and Gao et al[38] pointed out that there was no difference in the accuracy of pedicle screw placement between robot navigation and fluoroscopy guidance. Some scholars have also pointed out that robot-assisted pedicle screw placement is more accurate.[5] Therefore, in our meta-analysis, we included the number of pedicle screws without cortical invasion in each literature. meta-analysis showed that the accuracy of pedicle screw placement assisted by robot was higher than that under traditional fluoroscopy. In terms of radiation results, Kantelhardt et al[32] pointed out that the radiation time of robot-assisted screw placement is shorter than that of pedicle screw implantation under fluoroscopy. Roser et al[16] also pointed out that robot-assisted pedicle screw implantation reduced the fluoroscopy time by about half compared with traditional fluoroscopy. At the same time, it was reported that in the initial learning process, although there was no significant difference in fluoroscopy time between robot-assisted pedicle screw implantation and traditional fluoroscopy, the fluoroscopy time during operation could be reduced with familiarity with the robot. However, different number of pedicle screws, surgical experience and surgical methods will affect the change of radiation dose. Therefore, in this meta-analysis, we make a statistical analysis of the radiation index of each screw, and the results show that there is no statistical difference in the fluoroscopy time between robot-assisted pedicle screw implantation and traditional fluoroscopy. The accurate implantation of pedicle screws for the first time is very important to avoid the decrease of screw pullout force caused by adjusting the screw path. The evidence from our meta-analysis showed that robot-assisted pedicle screw placement was lower than fluoroscopic guidance in terms of screw adjustment rate. Kim et al[39] pointed out that the entry point of pedicle screw assisted by robot is more lateral, which can obtain a larger internal inclination angle and help to protect the joint capsule. Wang et al conducted Logistic regression analysis on the data of 237 cases, pointing out that the invasion of the articular process of the adjacent vertebral body during the operation was one of the important factors leading to adjacent spondylosis. This Meta shows that robot-assisted pedicle screw implantation is superior

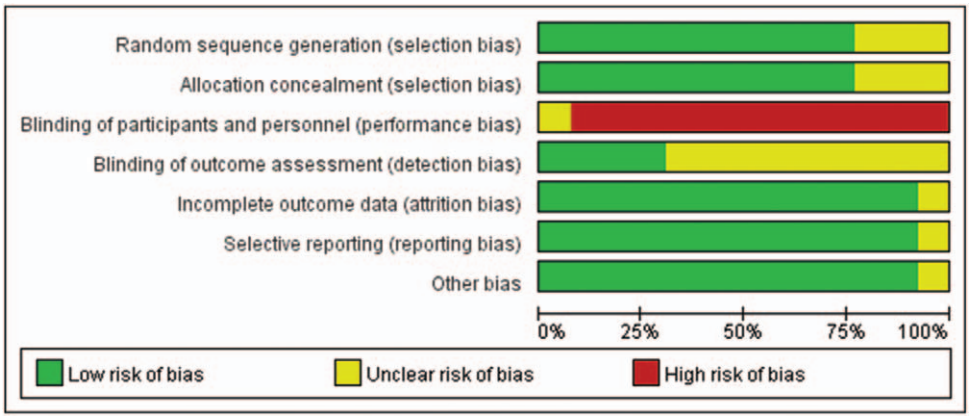

Figure 3. Risk of bias summary: review authors' judgements about each risk of bias item for each included study.

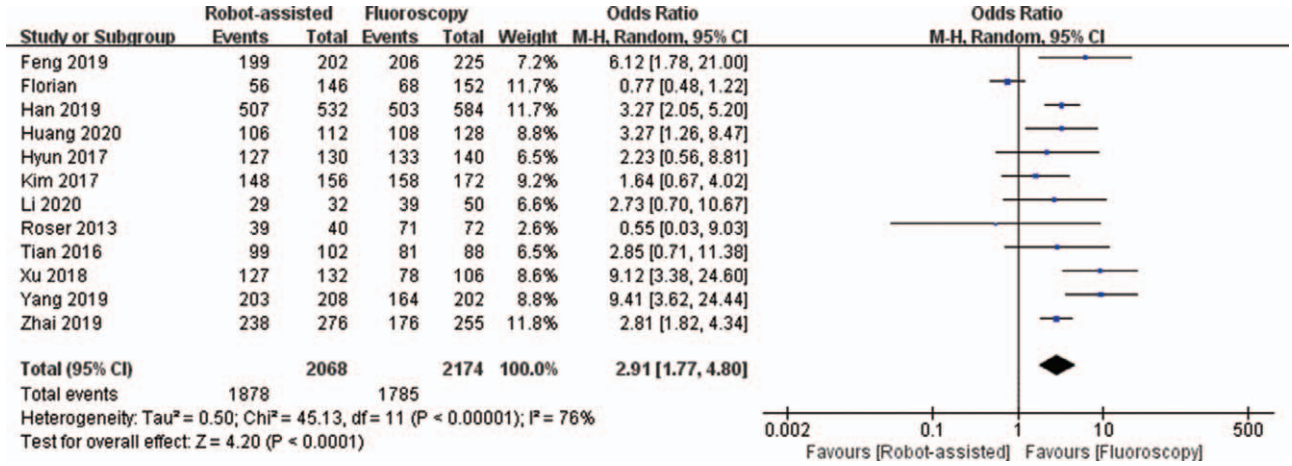

Figure 4. Forest plot of the comparison of the accuracy of pedicle screw placement between Robot-assisted and fluoroscopy.

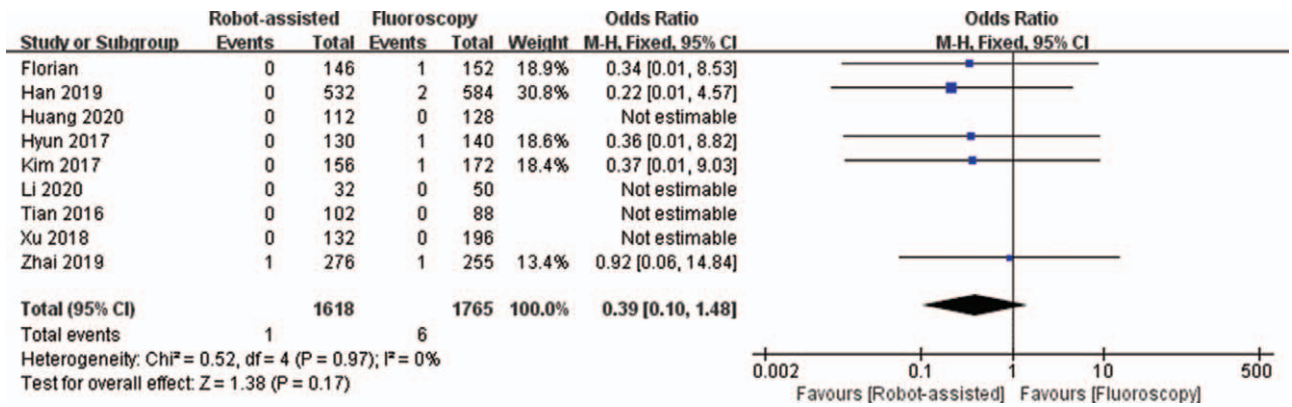

Figure 5. Forest plot of the comparison of complications caused by pedicle screw implantation between Robot-assisted and fluoroscopy.

to traditional fluoroscopy in the protection of facet joints. In terms of neurovascular injury caused by pedicle screw implantation, there was no statistical difference between robot-assisted and traditional fluoroscopic pedicle screw placement.

In this meta-analysis, we have some shortcomings. First of all, we did not consider the impact of minimally invasive or open on the accuracy of nail placement. Secondly, because of the different experience and methods of operation, there are no statistics on

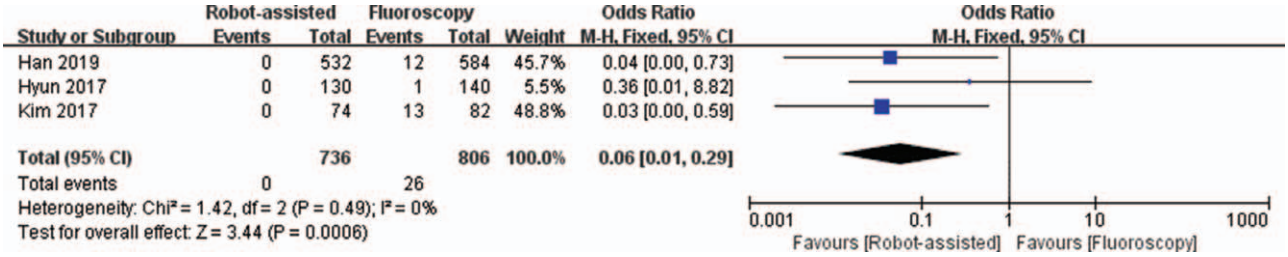

Figure 6. Forest plot of the comparison of facet joint invasion rate caused by pedicle screw implantation between Robot-assisted and fluoroscopy.

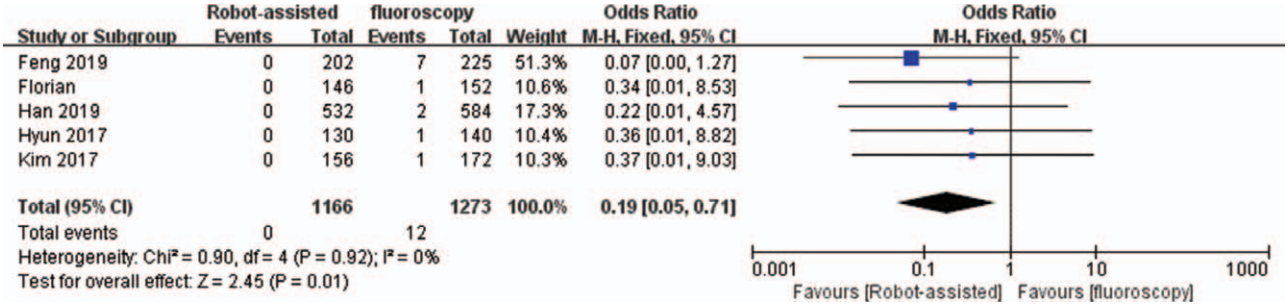

Figure 7. Forest plot of revision rate caused by pedicle screw implantation between Robot-assisted and fluoroscopy.

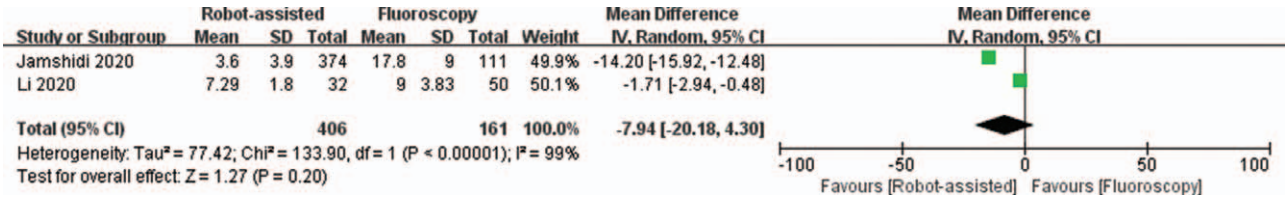

Figure 8. Forest plot of fluoroscopy time caused by pedicle screw implantation between Robot-assisted and fluoroscopy.

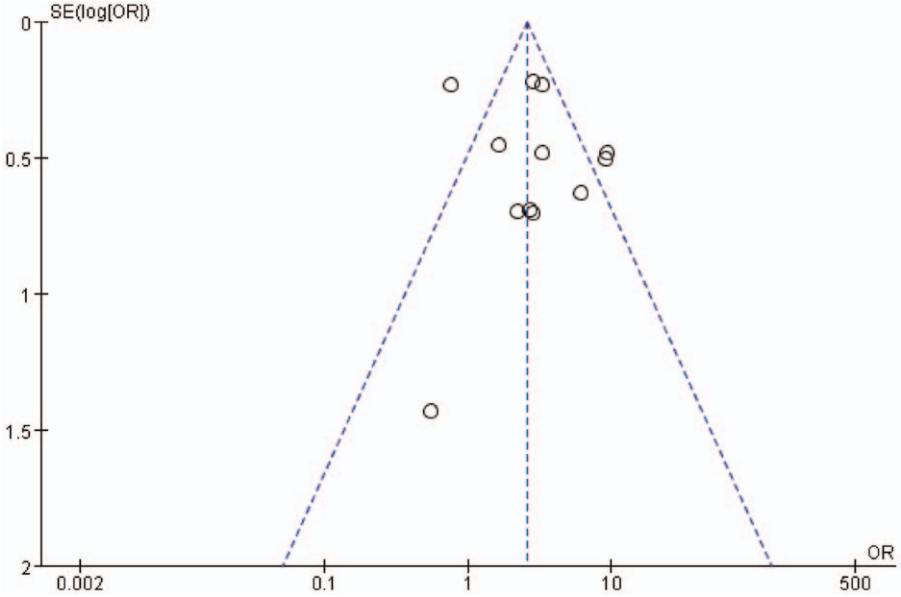

Figure 9. Funnel chart.

the time of operation, the amount of blood loss and so on. Finally, the risk of publication bias is widespread in meta-analysis, but we believe that our results are convincing and hope to get more high-quality randomized controlled trial in our future work.

6. Conclusion

This systematic review and meta-analysis provide evidence based on 13 randomized controlled trials comparing robot-assisted and conventional fluoroscope assisted placement of pedicle screws. The results showed that the accuracy of robot-assisted pedicle screw placement is higher than conventional fluoroscope assisted. In addition, the rate of facet joint invasion and revision rates by robot-assisted pedicle screw implantation was also significantly lower than fluoroscope assisted. However, there was no significant difference in the average radiation of pedicle screws and related complications between robot-assisted and fluoroscopy assisted in pedicle screw placement.

Author contributions

Data curation: Shangju Gao, Can Cao, Changren Li, Liang He, Xu Ma, Meng Li.
Investigation: chuntao li.
Methodology: Wenyi Li.
Resources: Shangju Gao, Can Cao.
Supervision: Wenyi Li.
Validation: Wenyi Li.
Writing – original draft: chuntao li.
Writing – review & editing: Wenyi Li.

References

[1] Makino T, Kaito T, Fujiwara H, Yonenobu K. Morphometric analysis using multiplanar reconstructed CT of the lumbar pedicle in patients with degenerative lumbar scoliosis characterized by a Cobb angle of 30° or greater. J Neurosurg Spine 2012;17:256–62.
[2] Laudato PA, Pierzchala K, Schizas C. Pedicle screw insertion accuracy using O-Arm, robotic guidance, or freehand technique: a comparative study. Spine (Phila Pa 1976) 2018;43:E373–8.
[3] Ringel F, Stüer C, Reinke A, et al. Accuracy of robot-assisted placement of lumbar and sacral pedicle screws: a prospective randomized comparison to conventional freehand screw implantation. Spine (Phila Pa 1976) 2012;37:E496–501.
[4] Kim HJ, Lee SH, Chang BS, et al. Monitoring the quality of robot-assisted pedicle screw fixation in the lumbar spine by using a cumulative summation test. Spine (Phila Pa 1976) 2015;40:87–94.
[5] Fan Y, Du JP, Liu JJ, et al. Accuracy of pedicle screw placement comparing robot-assisted technology and the free-hand with fluoroscopy-guided method in spine surgery: an updated meta-analysis. Medicine (Baltimore) 2018;97:e10970.
[6] Tarawneh AM, Salem KM. A systematic review and meta-analysis of randomized controlled trials comparing the accuracy and clinical outcome of pedicle screw placement using robot-assisted technology and conventional freehand technique. Global Spine J 2021;11:575–86.
[7] Zhou LP, Zhang RJ, Li HM, Shen CL. Comparison of cranial facet joint violation rate and four other clinical indexes between robot-assisted and freehand pedicle screw placement in spine surgery: a meta-analysis. Spine (Phila Pa 1976) 2020;45:E1532–40.
[8] Jie H, Bing H, Jixuan L, et al. Clinical effect for orthopaedic robot assisted minimally invasive lumbar internal fixation surgery. Beijing Biomedical Engineering 2020;39:145–51.
[9] Li Z, Chen J, Zhu QA, et al. A preliminary study of a novel robotic system for pedicle screw fixation: a randomised controlled trial. J Orthop Translat 2020;20:73–9.
[10] Feng S, Tian W, Sun Y, Liu Y, Wei Y. Effect of robot-assisted surgery on lumbar pedicle screw internal fixation in patients with osteoporosis. World Neurosurg 2019;125:e1057–62.
[11] Gongwei Z. Robot-assisted versus traditional posterior pedicle screw internal fixation in the treatment of scoliosis. Journal of Practical Diagnosis and Therapy 2019;33:636–40.
[12] Han X, Tian W, Liu Y, et al. Safety and accuracy of robot-assisted versus fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery: a prospective randomized controlled trial. Journal of Neurosurgery: Spine 2019;30:615–22.
[13] Rui Y, Yongqi L, Ke Z. Clinical application and experience of pedicle screw insertion assisted by tianjiorthopaedic robot. Journal of Practical Orthopaedics 2019;25:892–7.
[14] Peng X, Peng G, Ren-jie Z. Effect of robot assisted pedicle screw fixation in the treatment of thoracolumbar fracture. The Journal of Cervicodynia and Lumbodynia 2018;39:687–90.
[15] Wei T, Mingxing F, Xiaoguang H, Jingwei Z, Yajun L. Pedicle screw insertion in spine:a randomized comparison study of robot-assisted surgery and fluoroscopy-guided techniques. GUKE LINCHUANG YU YANJIU ZAZHI 2016;1:4–10.
[16] Roser F, Tatagiba M, Maier G. Spinal robotics: current applications and future perspectives. NEUROSURGERY 2013;72 Suppl 1:12–8.
[17] Hyun SJ, Kim KJ, Jahng TA, Kim HJ. Minimally invasive robotic versus open fluoroscopic-guided spinal instrumented fusions: a randomized controlled trial. Spine (Phila Pa 1976) 2017;42:353–8.
[18] Kim HJ, Jung WI, Chang BS, Lee CK, Kang KT, Yeom JS. A prospective, randomized, controlled trial of robot-assisted vs freehand pedicle screw fixation in spine surgery. Int J Med Robot 2017;13:
[19] Jamshidi AM, Massel DH, Liounakos JI, et al. Fluoroscopy time analysis of a prospective, multi-centre study comparing robotic- and fluoroscopic-guided placement of percutaneous pedicle screw instrumentation for short segment minimally invasive lumbar fusion surgery. Int J Med Robot 2020;e2188.
[20] Gaines RJ. The use of pedicle-screw internal fixation for the operative treatment of spinal disorders. J Bone Joint Surg Am 2000;82:1458–76.
[21] Ofiram E, Polly DW, Gilbert TJ, Choma TJ. Is it safer to place pedicle screws in the lower thoracic spine than in the upper lumbar spine? Spine (Phila Pa 1976) 2007;32:49–54.
[22] Tian W, Liu YJ, Liu B, et al. Guideline for thoracolumbar pedicle screw placement assisted by orthopaedic surgical robot. Orthop Surg 2019;11:153–9.
[23] Tang J, Zhu Z, Sui T, Kong D, Cao X. Position and complications of pedicle screw insertion with or without image-navigation techniques in the thoracolumbar spine: a meta-analysis of comparative studies. J Biomed Res 2014;28:228–39.
[24] Mason A, Paulsen R, Babuska JM, et al. The accuracy of pedicle screw placement using intraoperative image guidance systems. J Neurosurg Spine 2014;20:196–203.
[25] Goda Y, Higashino K, Toki S, et al. The pullout strength of pedicle screws following redirection after lateral wall breach or end-plate breach. Spine (Phila Pa 1976) 2016;41:1218–23.
[26] Onen MR, Naderi S. Robotic systems in spine surgery. Turk Neurosurg 2014;24:305–11.
[27] D'Souza M, Gendreau J, Feng A, Kim LH, Ho AL, Veeravagu A. Robotic-assisted spine surgery: history, efficacy, cost, and future trends. Robot Surg 2019;6:9–23.
[28] Lieberman IH, Togawa D, Kayanja MM, et al. Bone-mounted miniature robotic guidance for pedicle screw and translaminar facet screw placement: part I–Technical development and a test case result. Neurosurgery 2006;59:641–50.
[29] Huang M, Tetreault TA, Vaishnav A, York PJ, Staub BN. The current state of navigation in robotic spine surgery. Ann Transl Med 2021;9:86.
[30] L'Orsa R, Macnab CJ, Tavakoli M. Introduction to haptics for neurosurgeons. Neurosurgery 2013;72 Suppl 1:139–53.
[31] Joseph JR, Smith BW, Liu X, Park P. Current applications of robotics in spine surgery: a systematic review of the literature. Neurosurg Focus 2017;42:E2.
[32] Kantelhardt SR, Martinez R, Baerwinkel S, Burger R, Giese A, Rohde V. Perioperative course and accuracy of screw positioning in conventional, open robotic-guided and percutaneous robotic-guided, pedicle screw placement. EUR SPINE J 2011;20:860–8.
[33] Keric N, Eum DJ, Afghanyar F, et al. Evaluation of surgical strategy of conventional vs. percutaneous robot-assisted spinal trans-pedicular instrumentation in spondylodiscitis. J Robot Surg 2017;11:17–25.
[34] Molliqaj G, Schatlo B, Alaid A, et al. Accuracy of robot-guided versus freehand fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery. Neurosurg Focus 2017;42:E14.

[35] Schröder ML, Staartjes VE. Revisions for screw malposition and clinical outcomes after robot-guided lumbar fusion for spondylolisthesis. Neurosurg Focus 2017;42:E12.
[36] Yu L, Chen X, Margalit A, Peng H, Qiu G, Qian W. Robot-assisted vs freehand pedicle screw fixation in spine surgery - a systematic review and a meta-analysis of comparative studies. Int J Med Robot 2018;14:e1892.
[37] Liu H, Chen W, Wang Z, Lin J, Meng B, Yang H. Comparison of the accuracy between robot-assisted and conventional freehand pedicle screw placement: a systematic review and meta-analysis. Int J Comput Assist Radiol Surg 2016;11:2273–81.
[38] Gao S, Lv Z, Fang H. Robot-assisted and conventional freehand pedicle screw placement: a systematic review and meta-analysis of randomized controlled trials. EUR SPINE J 2018;27:921–30.
[39] Kim HJ, Jung WI, Chang BS, Lee CK, Kang KT, Yeom JS. A prospective, randomized, controlled trial of robot-assisted vs freehand pedicle screw fixation in spine surgery. Int J Med Robot 2017;13.