European Spine Journal
https://doi.org/10.1007/s00586-026-09896-z

RESEARCH

Global analysis and prospects of assisted pedicle screw placement surgery: a bibliometric study

Qiwen Bao[1] · Xuan Tang[1] · Xiao Gu[1] · Jingtao Peng[1] · Xiang Yao[1]

Received: 8 February 2025 / Revised: 19 February 2026 / Accepted: 24 March 2026

Abstract

Purpose Pedicle screw placement is transitioning from traditional navigation to an "Intelligence Era." This study aims to map the evolutionary trajectory of intelligent pedicle screw placement, identifying the paradigm shift from mechanical validation to multi-modal integration, and to uncover the underlying clinical drivers and future technological frontiers.

Methods A systematic bibliometric analysis was conducted using VOSviewer and CiteSpace. Literature was retrieved from the Web of Science Core Collection (WoSCC), focusing on the transformative period from 2019 to 2026. Following PRISMA guidelines, 474 core articles were included. Analyses encompassed annual publication trends, institutional collaboration, keyword clustering, and citation bursts.

Results The knowledge base is objectively delineated into two parallel domains: technology-centric hardware systems and pathology-centric clinical scenarios (e.g., minimally invasive surgery and osteoporosis). Longitudinal analysis reveals a structural transition. Early research was quantitatively dominated by mechanical execution metrics, with "accuracy" (frequency = 211) as the primary focus. Subsequently, the focus shifted toward implementation barriers, evidenced by strong bursts in "risk factors" (strength = 2.97), "complications," and "cost of care." The latest emergent indicators are exclusively led by multi-modal technologies, prominently featuring "augmented reality," "artificial intelligence," and "5G network."

Conclusion The field has fundamentally shifted from validating geometric precision to managing systemic complexities and patient-specific risks. The synergistic integration of augmented reality for in-situ visualization, artificial intelligence for cognitive planning, and 5G networks for remote connectivity represents the ultimate paradigm shift to overcome current ergonomic barriers and steep learning curves.

Keywords Pedicle screw placement · Bibliometric analysis · Augmented reality · Artificial intelligence · Surgical robotics

Introduction

Pedicle screw placement is the cornerstone of modern spinal instrumentation, serving as the gold standard for stabilizing the vertebral column in cases of trauma, deformity, and degeneration [1, 2]. However, the procedure remains technically demanding and inherently risky. Historical data indicate that the breach rate for free-hand placement can range from 10% to 40%, with potential consequences including neurovascular injury, cerebrospinal fluid leakage, and the need for revision surgery [3, 4]. Consequently, achieving "zero-tolerance" for placement errors has become the enduring pursuit of spinal surgery. While the introduction of fluoroscopy-based navigation significantly improved accuracy, it introduced new challenges: substantial intraoperative radiation exposure for both patients and surgical teams

Qiwen Bao and Xuan Tang contributed equally to this work.

✉ Xiang Yao
yaoxiang6266@163.com

Qiwen Bao
785163533@qq.com

Xuan Tang
2222313195@stmail.ujs.edu.cn

Xiao Gu
2505497983@qq.com

Jingtao Peng
pengjt2022@163.com

[1] The Affiliated People's Hospital of Jiangsu University, Zhenjiang, China

Published online: 31 March 2026

[5, 6], and the ergonomic limitation of "hand-eye separation," where surgeons must divert their attention from the surgical field to external monitors [7].

To address these limitations, the field has undergone a profound technological revolution since 2019, marking a paradigm shift from simple navigation to "intelligent assistance." This period witnessed the convergence of three disruptive technologies: Robotics, Augmented Reality (AR), and Artificial Intelligence (AI) [8]. The commercial launch of integrated robotic platforms (e.g., Mazor X Stealth Edition) in early 2019 transformed robotic arms from passive positioning tools into active, image-guided partners, significantly reducing the learning curve [9, 10]. Simultaneously, the clinical adoption of head-mounted displays, such as the Microsoft HoloLens, pioneered "holographic navigation," effectively resolving the hand-eye coordination dilemma [11, 12]. Furthermore, the integration of deep learning algorithms for automated trajectory planning has begun to reshape preoperative workflows [13, 14], moving the field towards personalized precision medicine [15, 16]. These advancements have collectively defined the years 2019 to 2026 as the "Intelligence Era" of spinal surgery.

Despite the rapid evolution of these technologies, existing bibliometric studies on spinal navigation often span broad timeframes (e.g., 2000–2024), inadvertently diluting current trends with outdated data on early fluoroscopic technique [17, 18]. Few studies have specifically isolated the "Intelligence Era" to map the distinct evolutionary trajectories of robotics, AI, and AR. To fill this gap, this study employs CiteSpace and VOSviewer to conduct a comprehensive bibliometric analysis of 474 high-quality articles published between January 2019 and February 2026 [19, 20]. By filtering out historical noise, we aim to provide a high-resolution landscape of the global research hotspots, collaborative networks, and emerging frontiers in smart pedicle screw placement, offering a precise roadmap for future clinical and engineering innovations.

Methods

Literature database

To systematically map the paradigm shift toward the "Intelligence Era" in spinal surgery, this study designed a bibliometric and visual analytics framework based on citation and keyword co-occurrence. The research strategy was structured across three logical levels:

1) Macro-level: Evaluating the global spatiotemporal distribution of research productivity and collaborative networks among institutions.
2) Meso-level: Utilizing keyword clustering to uncover the structural relationships among core technological themes (e.g., Robotics, Artificial Intelligence, and Augmented Reality).
3) Micro-level: Applying burst detection and timeline views to trace the evolutionary trajectory of specific techniques and predict future clinical frontiers.

Literature analysis method

Data Source and Variables: Data were exclusively retrieved from the Web of Science Core Collection (WoSCC) on February 10, 2026. The WoSCC database is widely recognized for its high-quality data structure, comprehensive citation indexing, and strict standardization, making it the most ideal and frequently utilized database for bibliometric analyses [21].

Search Strategy and Scope: To explicitly capture the intelligent technological wave, the temporal scope was strictly defined from January 1, 2019, to February 10, 2026. The search query was formulated by combining anatomical targets with advanced technological interventions: TS = ("Pedicle screw" OR "Spinal instrumentation") AND TS = ("Navigation" OR "Robotics" OR "Augmented Reality" OR "Artificial Intelligence" OR "Computer-assisted surgery" OR "Deep Learning").

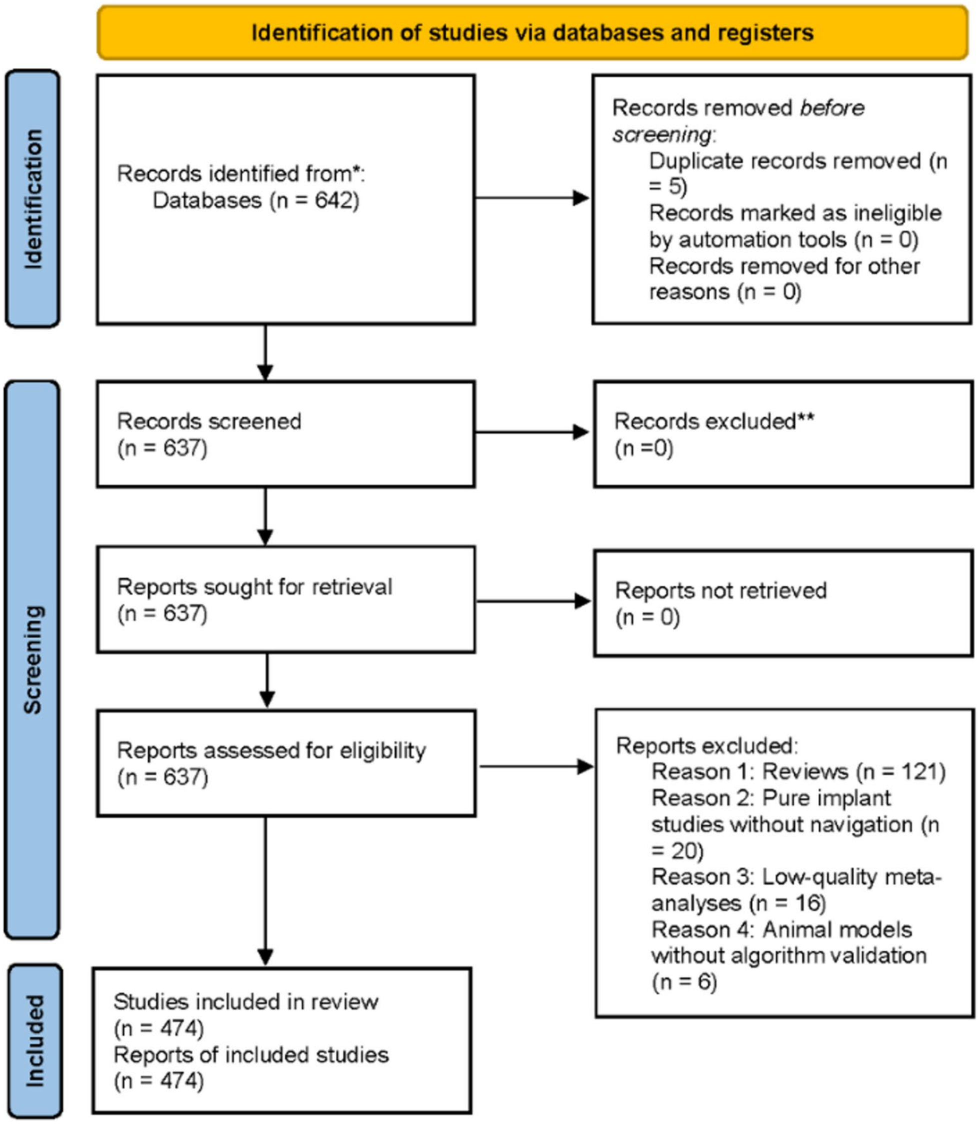
Inclusion, Exclusion, and Screening: Only "Articles" and "Reviews" published in English were included. Studies purely focusing on implant biomechanics without navigational systems, animal models unrelated to algorithm validation, and low-quality meta-analyses were excluded. The literature screening process was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [22]. The initial query yielded 642 records. Following a rigorous manual screening of titles and abstracts by two independent researchers to ensure topic relevance, a final dataset comprising 474 core articles was established for subsequent topological analysis.

Table 1. PRISMA flow diagram detailing the literature search, screening, and inclusion process for this bibliometric study. The search was conducted in the Web of Science Core Collection (WoSCC), yielding an initial 642 records. After rigorous screening, a final dataset of 474 core articles was included for visual and statistical analysis.

Inclusion and exclusion criteria

Bibliometric mapping and statistical inferences were conducted using VOSviewer (version 1.6.20) and CiteSpace (version 6.4.R1).

Table 1 PRISMA flow diagram of the literature search and selection process



Network Construction (VOSviewer): Employed for institutional collaboration and keyword co-occurrence analyses. The software uses probability-based normalization to establish network nodes and links, weighted by occurrence frequency and Total Link Strength (TLS), thereby identifying the core driving forces in the field [20].

Evolutionary Modeling and Validation (CiteSpace): Utilized to generate Timeline views and execute Burst detection based on set-theoretic data normalization [19].

Model Configuration: The time slicing was set to 1 year per slice (2019–2026). The g-index (k=21) was applied as the selection criterion to filter high-frequency representative nodes.

Network Pruning: To eliminate redundant connections and optimize the clarity of the topological structure, the Pathfinder algorithm and "Pruning sliced networks" were applied [19].

Evaluation Metrics: The statistical reliability of the keyword clustering model was validated using two critical metrics: the Modularity Q and the Mean Silhouette S. In our established model, the network achieved a Modularity $Q>0.5$ (indicating a significant clustering structure) and a Silhouette $S>0.7$ (confirming high homogeneity and credibility within clusters).

Results

Annual publication output and growth trend

Following the PRISMA guidelines (Table 1), 474 core articles were included. The annual publication trend analysis (Fig. 1) focused on 465 articles published between 2019 and

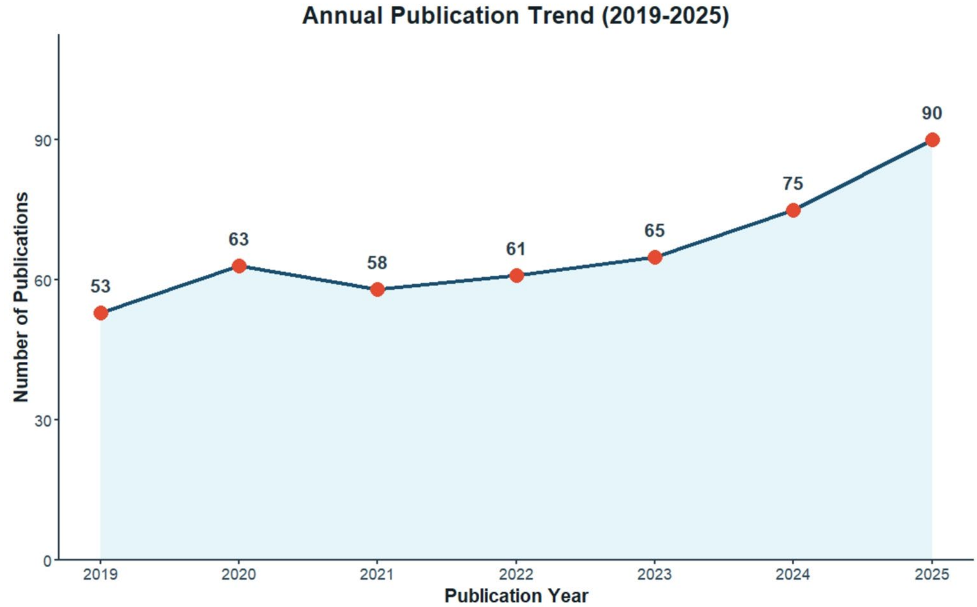


Fig. 1 Annual Publication Output and Growth Trend

Table 2 Top 10 most productive countries/regions based on publication volume and betweenness centrality

Rank	Country/Region	Publications (*n*)	Centrality	First Year
1	USA	150	0.72	2019
2	PEOPLES R CHINA	143	0.00	2019
3	GERMANY	41	0.17	2019
4	SWITZERLAND	36	0.26	2019
5	JAPAN	24	0.00	2019
6	NETHERLANDS	18	0.06	2019
7	CANADA	17	0.28	2019
8	SWEDEN	16	0.00	2019
9	ITALY	13	0.16	2019
10	INDIA	13	0.25	2019

(Betweenness centrality > 0.1 is typically considered as an important hub in the co-authorship network.)

2025. The data indicates a steady publication volume from 2019 to 2023, averaging approximately 60 articles annually. An upward trend was observed subsequently, with publications increasing to 75 in 2024 and reaching 90 in 2025.

Figure 1. Annual publication trends of intelligent pedicle screw placement research from 2019 to 2025. The continuous upward trajectory, particularly the significant surge observed in 2024 and 2025, illustrates the accelerating clinical integration of navigation, artificial intelligence, and robotic technologies in spinal surgery. (Note: To present complete yearly cycles, 9 articles published in early 2026 were excluded from this trend chart, though they remain included in the overall bibliometric network analysis.)

National distribution and centrality

Table 2 details the top 10 most productive countries/regions. Based on publication volume, the United States (150 publications) and China (143 publications) were the primary contributors. In terms of betweenness centrality—a metric reflecting international collaborative influence—the United States exhibited the highest value (0.72). In contrast, China recorded a centrality of 0.00, indicating a co-authorship network primarily concentrated within domestic institutions. Other countries, such as Switzerland (Centrality = 0.26) and Canada (Centrality = 0.28), demonstrated high collaborative centrality relative to their publication output.

Core authors and co-authorship networks

Following name disambiguation, the top 10 most productive authors were identified (Table 3). Mazda Farshad (23 publications) and Philipp Fürnstahl (21 publications) recorded the highest publication volumes. In terms of total citations, Erik Edström (705 citations, 16 publications) was the most highly cited author. The co-authorship network, as measured by Total Link Strength (TLS), reveals that high-TLS clusters are predominantly formed within specific institutional or national groups, such as the Swiss team (Farshad and Fürnstahl), the Swedish team (Edström and Burström), and the Chinese team (Tian, Han, and Liu).

Keyword clustering analysis

Keyword clustering analysis yielded 7 major clusters (Fig. 3). Based on the extracted cluster labels, the network can be categorized into two primary themes. The first theme relates to hardware and systemic configurations, encompassing Cluster #2 (robot-assisted surgery), #3 (surgical robotics), and #6 (mechatronic systems). The second theme focuses on surgical applications and clinical parameters,

Table 3 Top 10 most productive authors and their collaboration metrics in intelligent pedicle screw placement research

Rank	Author	Affiliation (Country)	Documents	Citations
1	Farshad, Mazda	Balgrist Univ Hosp (Switzerland)	23	618
2	Fürnstahl, Philipp	Univ of Zurich (Switzerland)	21	617
3	Edström, Erik	Karolinska Inst (Sweden)	16	705
4	Tian, Wei	Jishuitan Hosp (China)	14	581
5	Burström, Gustav	Karolinska Inst (Sweden)	13	623
6	Elmi-Terander, Adrian	Karolinska Inst (Sweden)	13	497
7	Han, Xiaoguang	Jishuitan Hosp (China)	11	446
8	Liu, Yajun	Jishuitan Hosp (China)	10	471
9	He, Da	Jishuitan Hosp (China)	10	427
10	Liu, Bo	Jishuitan Hosp (China)	10	421

(To ensure the accuracy of the bibliometric analysis, publication counts and citations for authors with variant name spellings in the WoSCC database (e.g., Philipp Fürnstahl, Xiaoguang Han, and Yajun Liu) have been manually verified and merged.)

including Cluster #0 (minimally invasive spine surgery), #1 (lateral surgery), #4 (spinal fusion), and #5 (spine surgery). The emergence of terms such as "accuracy," "complications," and "osteoporosis" within these clusters reflects the targeted clinical metrics in current navigation and robotic studies.

Figure 2. Keyword clustering network map of intelligent pedicle screw placement research. The 7 distinct clusters illustrate a dual-track development in the field: the engineering advancement of intelligent mechatronic/robotic systems, and their targeted clinical application in complex scenarios such as minimally invasive procedures and osteoporotic spinal fusions.

Thematic evolution and emerging research frontiers

The temporal evolution of the knowledge domain is visualized in the timeline view (Fig. 3). Cluster #0 (spinal fusion) and #4 (pedicle screw fixation) demonstrate a chronological shift from foundational imaging terms (e.g., intraoperative CT, 2019–2020) to algorithmic concepts (e.g., machine learning, 2022–2023). Keyword citation burst analysis (Fig. 4) quantifies this shift. Early high-burst keywords included "feasibility" (2019–2020) and "clinical accuracy" (2021–2023). In the most recent period (2024–2026), the keywords with the strongest ongoing bursts are "risk factors" (Strength = 2.97),

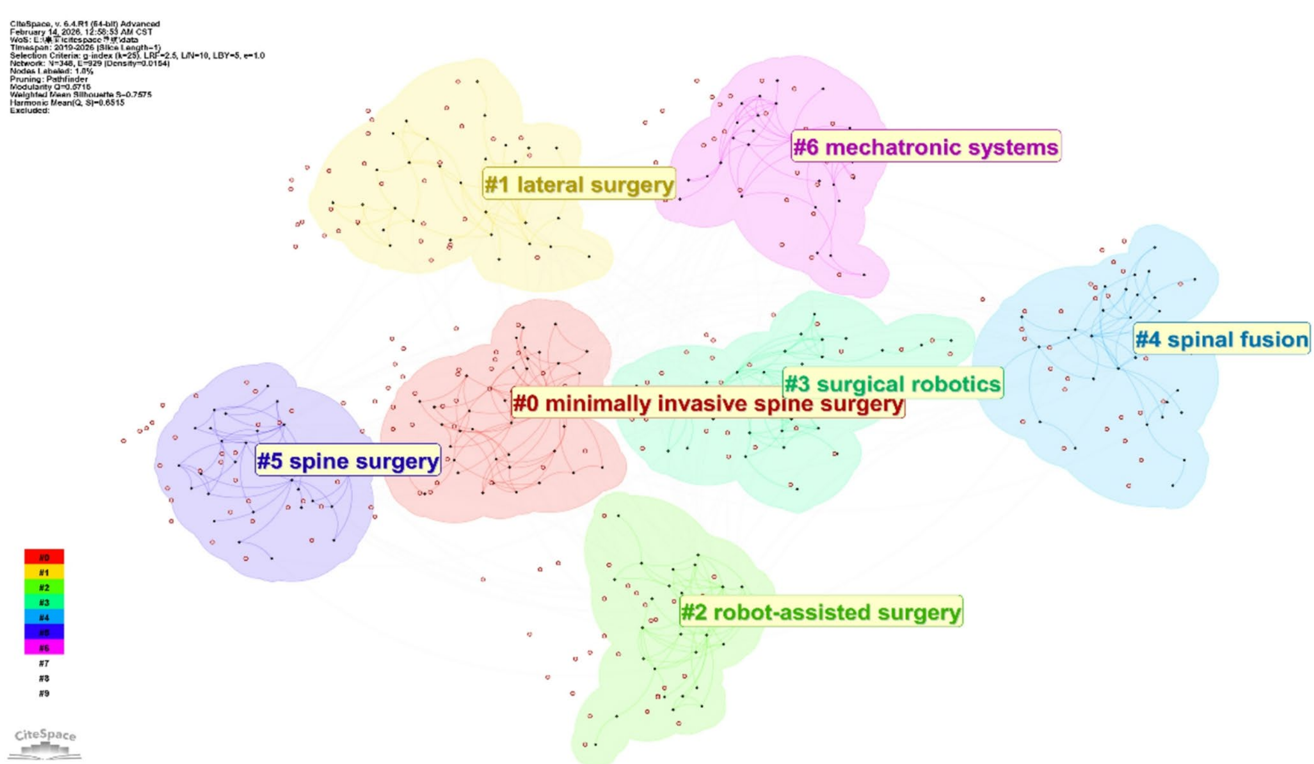


Fig. 2 Keyword clustering network map of intelligent pedicle screw placement research

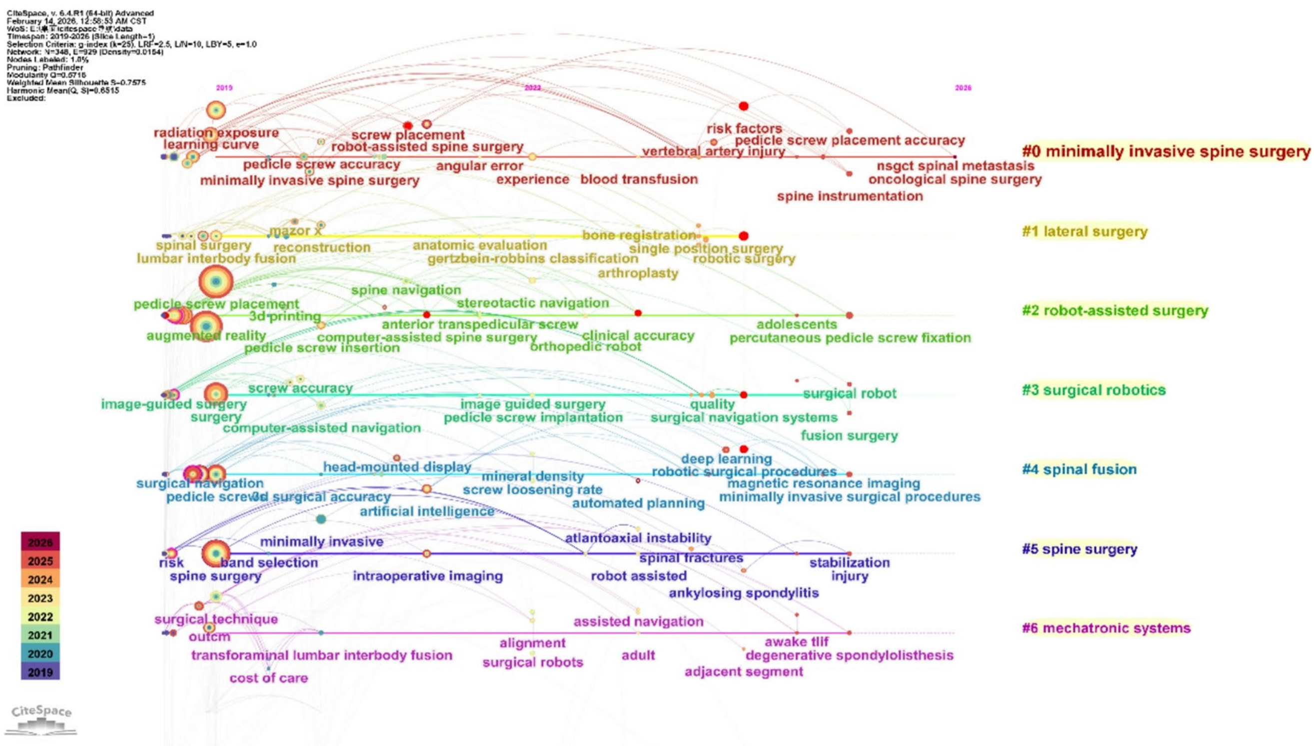


Fig. 3 Timeline view of keyword clusters in intelligent pedicle screw placement research

Fig. 4 Top 10 keywords with the strongest citation bursts in the field

"robotic surgery" (Strength = 2.97), and "surgical navigation systems" (Strength = 2.22).

Figure 3. Timeline view of keyword clusters in intelligent pedicle screw placement research. The horizontal axis represents time, and nodes are positioned based on their first appearance year. Major clusters, such as #0 (spinal fusion) and #4 (pedicle screw fixation), reveal a clear progression from basic navigation topics in earlier years towards intelligent planning and risk-related concerns in recent years.

Figure 4. Top 10 keywords with the strongest citation bursts in the field. The red segments represent the time intervals where the keyword frequency increased significantly. The shift from early "feasibility" terms to recent strong bursts in "robotic surgery" and "risk factors" (ongoing through 2026) highlights the current transition towards intelligent integration and risk stratification.

Reference co-citation analysis and intellectual base

Reference co-citation analysis identifies the foundational literature based on citation frequency (Table 4). The most highly co-cited reference is Gertzbein et al. (1990) with 174 co-citations, which established the grading system for pedicle screw placement. The remaining top 10 co-cited references, published between 2010 and 2019,

Table 4 Top 10 most highly co-cited references in the field of intelligent pedicle screw placement

Rank	First Author	Year	Source Journal		Co-citations
1	Gertzbein SD	1990	*Spine*	Accuracy of pedicular screw placement in vivo	174
2	Hyun SJ	2017	*Spine*	Minimally invasive robotic versus open fluoroscopic-guided spinal instrumented fusions: a randomized controlled trial	64
3	Kantelhardt S	2011	*Eur Spine J*	Perioperative course and accuracy of screw positioning in conventional, open robotic-guided and percutaneous robotic-guided, pedicle screw placement	60
4	Ringel F	2012	*Spine*	Accuracy of robot-assisted placement of lumbar and sacral pedicle screws: a prospective randomized comparison to conventional freehand fluoroscopy-guided placement	56
5	Gelalis ID	2012	*Eur Spine J*	Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques	54
6	Mason A	2014	*J Neurosurg-Spine*	The accuracy of pedicle screw placement using intraoperative image guidance systems	54
7	Han XG	2019	*J Neurosurg-Spine*	Safety and accuracy of robot-assisted versus fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery: a prospective randomized controlled trial	53
8	Molliqaj G	2017	*Neurosurg Focus*	Accuracy of robot-guided versus freehand fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery	52
9	Van Dijk JD	2015	*Spine*	Clinical pedicle screw accuracy and deviation from planning in robot-guided spine surgery	51
10	Devito DP	2010	*Spine*	Clinical acceptance and accuracy assessment of spinal implants guided with SpineAssist surgical robot: retrospective study	47

primarily consist of systematic reviews and randomized controlled trials (e.g., Hyun SJ, 2017; Kantelhardt S, 2011) that compare the clinical accuracy and safety of robot-assisted or navigation-guided placement against conventional freehand techniques.

Discussion

The "accuracy paradox" and risk stratification

The critical nature of accurate pedicle screw placement cannot be overstated, as it directly impacts patient outcomes, significantly reduces the risk of neurological complications, and minimizes the likelihood of revision surgeries [23, 24]. Historically, this pursuit of optimal spinal fixation has driven a continuous evolution from conventional C-arm fluoroscopy and early minimally invasive techniques toward modern intelligent platforms. The bibliometric trajectory of intelligent pedicle screw placement demonstrates a significant publication surge post-2019. Early literature was fundamentally driven by technical feasibility [2, 25–28], with foundational randomized controlled trials (RCTs) robustly validating the superior accuracy of robotic systems over freehand techniques [9, 29–32]. Consequently, validation metrics dominated this era, with "accuracy" (frequency = 211) acting as the primary keyword. However, our burst analysis reveals a recent cessation in the burst of "accuracy," rapidly superseded by "risk factors" (Strength = 2.97) and "complications" (frequency = 46) [33, 34].

This longitudinal shift highlights the "accuracy paradox." Current mechatronic systems have reached a plateau in geometric precision; yet, perfect anatomical execution does not intrinsically guarantee a complication-free outcome [35–37]. The fundamental mechanism behind this shift is the transition of clinical challenges from the hardware's execution capability to the systemic risks introduced by technological complexity in advanced procedures (e.g., MIS and lateral surgery) [8, 38, 39]. In complex scenarios, such as osteoporotic fractures, achieving reliable fixation has historically necessitated supplementary techniques like electromyography (EMG) guidance and cement augmentation to ensure safety [40]. Today, complications in modern navigated procedures predominantly arise from prolonged operative times, registration failures, and compromised spatial orientation rather than simple trajectory deviation [41, 42].

Therefore, achieving sub-millimeter precision is no longer the sole endpoint; contemporary intelligent spine surgery must prioritize patient-specific risk stratification and systemic complication management over mere technical execution.

Clinical disconnect and implementation barriers

While the shift towards risk stratification explains the evolving clinical focus, our keyword clusters expose the systemic barriers hindering widespread adoption. The lateral comparison reveals a stark contrast between high-end hardware (Cluster #2: robot-assisted surgery) and the emergence of "cost of care" (emerging in 2020) alongside "complications" [43, 44].

The underlying driver of this disconnect is the friction between technological capability and real-world surgical ergonomics [45, 46]. The progressive integration of technology into minimally invasive procedures (e.g., multi-level mini-open TLIF) was originally intended to enhance intraoperative safety and streamline the surgical workflow [47]. Paradoxically, contemporary robotic systems often require disruptive workflow alterations, bulky operating room setups, and prolonged registration protocols [48–50]. Furthermore, as corroborated by implementation science, the formidable economic burden and the steep cognitive learning curve represent massive barriers [51–53]. Surgeons face a paradoxical situation where the technology designed to reduce operative risk simultaneously introduces new logistical loads during the initial adoption phase [54].

Ultimately, the widespread integration of current robotic systems is severely bottlenecked by ergonomic and economic infeasibility, necessitating a shift toward more intuitive, less disruptive surgical assistance modalities.

The future paradigm of AR, AI, and 5G integration

Driven by the need to overcome these ergonomic and cognitive limitations, the bibliometric data points toward a highly integrated future. Our timeline identifies a massive surge in "augmented reality" (AR) (frequency = 99), alongside the emergence of "3D image guidance" and "5G network" by 2025 [54].

These technologies target specific mechanisms of surgical failure. AR directly resolves the "hand-eye coordination" problem of traditional navigation by projecting 3D anatomical models and planned trajectories directly onto the surgical site via head-mounted displays, restoring the surgeon's natural focus and reducing operating room clutter [55–57]. Concurrently, Artificial Intelligence (AI) algorithms serve as the cognitive engine, automating preoperative planning to proactively avoid trajectory-related risk factors [14, 58]. Finally, the ultra-low latency of 5G networks facilitates cloud-based computing and zero-latency tele-mentoring [59–61], directly flattening the steep learning curve for junior surgeons [62, 63].

The synergistic integration of AR (for ergonomic execution), AI (for cognitive planning), and 5G (for global connectivity) represents the ultimate paradigm shift, democratizing high-precision pedicle screw placement and resolving current implementation barriers.

Limitations and future perspectives

While this study provides the first comprehensive bibliometric mapping of intelligent pedicle screw placement over a 20-year span, several limitations must be objectively acknowledged.

First, regarding limitations in scope, the search strategy was strictly confined to "pedicle screw placement" to maintain high specificity. Consequently, broader applications of intelligent spinal technologies (e.g., robotic osteotomies or AI-driven diagnostic imaging) were deliberately excluded, which may limit the generalizability of our findings across the entire spectrum of spine surgery.

Second, regarding limitations in data and methodology, the retrieval was restricted to the Web of Science Core Collection (WoSCC) to ensure formatting compatibility with VOSviewer and CiteSpace, potentially omitting relevant literature indexed solely in Scopus or PubMed. Furthermore, bibliometric algorithms primarily analyze metadata (titles, abstracts, and keywords) rather than full-text semantics, occasionally overlooking nuanced methodological or biomechanical details. Additionally, owing to the inherent temporal lag of citation dynamics, highly impactful studies published recently (e.g., 2023–2024) may not have accumulated sufficient citations to appear prominently in the co-citation networks.

Based on these limitations and our current findings, future studies should adopt a multi-database fusion approach to broaden the data scope. Methodologically, transitioning from traditional bibliometrics to Natural Language Processing (NLP) models capable of full-text semantic extraction will be crucial for uncovering deep technical details. Clinically, our predictions urgently call for prospective, multi-center studies to validate the actual efficacy, cost-effectiveness, and learning-curve reduction of the proposed "AR-AI-5G" synergistic paradigm in real-world operating rooms.

Table 5 Summary of Core Bibliometric Indicators and Evolutionary Phases in Intelligent Pedicle Screw Placement

Evolutionary Phase	Primary Indicator Category	Objective Core Nodes (Extracted Metrics)	Defined Research Focus
Phase I: Mechanical Validation (<2019)	Efficacy & Feasibility Indicators	"Accuracy" (Freq: 211) "Feasibility" (Burst: 2017–2021)	Validation of geometric trajectory precision and fundamental anatomical safety of hardware.
Phase II: Implementation Bottlenecks (2020–2024)	Systemic & Clinical Barrier Indicators	"Complications" (Freq: 46) "Risk factors" (Strength: 2.97) "Cost of care" (Node: 2020)	Identification of clinical disconnects in complex scenarios (e.g., MIS, osteoporosis), including learning curves.
Phase III: Multi-modal Integration (2024–2026)	Emerging Frontier Indicators	"Augmented reality" (Freq: 99) "5G network" (Burst to 2025) "Artificial intelligence" (Cluster #2)	Structural transition towards in-situ visualization, automated cognitive planning, and remote connectivity.

Conclusion

This study employed VOSviewer and CiteSpace to systematically extract and analyze 474 literature records from the Web of Science Core Collection (2004–2024) regarding intelligent pedicle screw placement. The bibliometric indicators collectively re-abstract a 20-year evolutionary trajectory of the field, marking a structural transition from the validation of mechanical precision to the management of systemic complexities in clinical adoption.

Categorized by clustering and co-citation indicators, the knowledge base is objectively delineated into two parallel domains: technology-centric hardware systems (Cluster #2: robot-assisted surgery; Cluster #6: mechatronic systems) and pathology-centric clinical scenarios (Cluster #0: minimally invasive surgery; Cluster #5: osteoporosis).

Longitudinal keyword indicators (bursts and timelines) further map the temporal evolution of research frontiers. Early bibliometric outputs were quantitatively dominated by execution metrics ("accuracy," frequency = 211). A subsequent shift in indicators highlights implementation variables, evidenced by nodes such as "complications" (frequency = 46), "cost of care" (emerging node in 2020), and "risk factors" (burst strength = 2.97). The latest emergent indicators (projected through 2025/2026) are exclusively led by multi-modal and non-mechanical technologies, with "augmented reality" (frequency = 99), "artificial intelligence," and "5G network" forming the contemporary frontier array. The core bibliometric results and metric transitions are summarized in Table 5.

Acknowledgements The data supporting the findings of this study were retrieved from the Web of Science database. Due to licensing agreements, the raw data cannot be shared publicly. However, interested researchers can access the data by obtaining the necessary subscriptions or access rights to the Web of Science database. For more information on accessing the Web of Science, please visit https://www.webofscience.com.

Author contributions In this study, the authors contributed as follows: Q.B.: Responsible for conceptualization, methodology, software development, resources, data curation, original draft preparation, and visualization.X.G. and J.P.: Conducted validation of the study results.Q.B. and X.T.: Involved in writing, reviewing, and editing the manuscript.X.Y.: Provided supervision, managed the project administration.All authors reviewed the manuscript. This statement clearly delineates the specific contributions of each author to the research project.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Kim YJ, Lenke LG, Bridwell KH et al (2004) Free hand pedicle screw placement in the thoracic spine: is it safe? [J]. Spine (Phila Pa 1976), 29(3): 333 – 42.
2. Gertzbein SD, Robbins SE (1990) Accuracy of pedicular screw placement in vivo [J]. Spine (Phila Pa 1976) 15(1):11–14
3. Laine T, Lund T, Ylikoski M et al (2000) Accuracy of pedicle screw insertion with and without computer assistance: a randomised controlled clinical study in 100 consecutive patients [J]. Eur Spine J 9(3):235–240
4. Kosmopoulos V, Schizas C (2007) Pedicle screw placement accuracy: a meta-analysis [J]. Spine (Phila Pa 1976) 32(3):E111–E120
5. Rampersaud YR, Foley KT, Shen AC et al (2000) Radiation exposure to the spine surgeon during fluoroscopically assisted pedicle screw insertion [J]. Spine (Phila Pa 1976) 25(20):2637–2645
6. Gao S, Lv Z, Fang H (2018) Robot-assisted and conventional freehand pedicle screw placement: a systematic review and meta-analysis of randomized controlled trials [J]. Eur Spine J 27(4):921–930
7. Meola A, Cutolo F, Carbone M et al (2017) Augmented reality in neurosurgery: a systematic review [J]. Neurosurg Rev 40(4):537–548
8. Zhang Q, Han XG, Fan MX et al (2023) Robotic navigation during spine surgery: an update of literature [J]. Expert Rev Med Devices 20(6):427–432
9. Han X, Tian W, Liu Y et al (2019) Safety and accuracy of robot-assisted versus fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery: a prospective randomized controlled trial [J]. J Neurosurg Spine 30(5):615–622
10. Kam JKT, Gan C, Dimou S et al (2019) Learning Curve for Robot-Assisted Percutaneous Pedicle Screw Placement in Thoracolumbar Surgery [J]. Asian Spine J 13(6):920–927
11. Elmi-Terander A, Burström G, Nachabe R et al (2019) Pedicle Screw Placement Using Augmented Reality Surgical Navigation

With Intraoperative 3D Imaging: A First In-Human Prospective Cohort Study [J]. Spine (Phila Pa 1976) 44(7):517–525
12. Molina CA, Theodore N, Ahmed AK et al (2019) Augmented reality-assisted pedicle screw insertion: a cadaveric proof-of-concept study [J]. J Neurosurg Spine 31(1):139–146
13. Khan M, Ahuja K, Tsirikos AI (2025) AI and machine learning in paediatric spine deformity surgery [J]. Bone Jt Open 6(5):569–581
14. Charles YP, Lamas V, Ntilikina Y (2023) Artificial intelligence and treatment algorithms in spine surgery [J]. Orthop Traumatol Surg Res 109(1s):103456
15. Galbusera F, Casaroli G, Bassani T (2019) Artificial intelligence and machine learning in spine research [J]. JOR Spine 2(1):e1044
16. Ali IS, Bakaes Y, Macleod JS et al (2025) Artificial Intelligence in Planning for Spine Surgery [J]. Curr Rev Musculoskelet Med 18(12):627–634
17. Mualem W, Onyedimma C, Ghaith AK et al (2022) R2 advances in robotic-assisted spine surgery: comparative analysis of options, future directions, and bibliometric analysis of the literature [J]. Neurosurg Rev 46(1):18
18. González-González F, Aguilar-Chávez F, Martínez-Loya C et al (2024) Top 100 Most Cited Articles on Intraoperative Image-Guided Navigation in Spine Surgery [J]. Cureus 16(8):e67950
19. Van Eck NJ, Waltman L (2010) Software survey: VOSviewer, a computer program for bibliometric mapping [J]. Scientometrics 84(2):523–538
20. Chen CM, CiteSpace II (2006) Detecting and visualizing emerging trends and transient patterns in scientific literature [J]. J Am Soc Inform Sci Technol, 57(3):359–377
21. Birkle C, Pendlebury DA, Schnell J et al (2020) Web of Science as a data source for research on scientific and scholarly activity [J]. Quant Sci Stud 1(1):363–376
22. Page MJ, Mckenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews [J]. BMJ 372:n71
23. Visocchi M, Conforti G, La Rocca G et al (2014) Invasive and mini-invasive lumbar fusions. Does exist a state of art? An enigma in search of solutions [J]. J Neurosurg Sci 58(2 Suppl 1):113–117
24. Tumbiolo S, Gerardi RM, Brunasso L et al (2023) Pedicle Screw Placement Aided by C-Arm Fluoroscopy: A Nevermore without Technology to Pursue Optimal Spine Fixation [J]. Acta Neurochir Suppl 135:213–217
25. Hyun SJ, Kim KJ, Jahng TA et al (2017) Minimally Invasive Robotic Versus Open Fluoroscopic-guided Spinal Instrumented Fusions: A Randomized Controlled Trial [J]. Spine (Phila Pa 1976) 42(6):353–358
26. Kantelhardt SR, Martinez R, Baerwinkel S et al (2011) Perioperative course and accuracy of screw positioning in conventional, open robotic-guided and percutaneous robotic-guided, pedicle screw placement [J]. Eur Spine J 20(6):860–868
27. Ringel F, Stüer C, Reinke A et al (2012) Accuracy of robot-assisted placement of lumbar and sacral pedicle screws: a prospective randomized comparison to conventional freehand screw implantation [J]. Spine (Phila Pa 1976) 37(8):E496–501
28. Gelalis ID, Paschos NK, Pakos EE et al (2012) Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques [J]. Eur Spine J 21(2):247–255
29. Mason A, Paulsen R, Babuska JM et al (2014) The accuracy of pedicle screw placement using intraoperative image guidance systems [J]. J Neurosurg Spine 20(2):196–203
30. Molliqaj G, Schatlo B, Alaid A et al (2017) Accuracy of robot-guided versus freehand fluoroscopy-assisted pedicle screw insertion in thoracolumbar spinal surgery [J]. Neurosurg Focus 42(5):E14
31. Van Dijk JD, Van Den Ende RP, Stramigioli S et al (2015) Clinical pedicle screw accuracy and deviation from planning in robot-guided spine surgery: robot-guided pedicle screw accuracy [J]. Spine (Phila Pa 1976) 40(17):E986–E991
32. Devito DP, Kaplan L, Dietl R et al (2010) Clinical acceptance and accuracy assessment of spinal implants guided with SpineAssist surgical robot: retrospective study [J]. Spine (Phila Pa 1976) 35(24):2109–2115
33. Lai MC, Sundaram PPM, Kaliya-Perumal AK et al (2025) Robotic spine surgery - Surgical technique and nuances for improving safety [J]. Biomed (Taipei) 15(1):1–5
34. Xu D, Ma X, Xie L et al (2023) Surgical Precision and Efficiency of a Novel Electromagnetic System Compared to a Robot-Assisted System in Percutaneous Pedicle Screw Placement of Endo-LIF [J]. Global Spine J 13(5):1243–1251
35. Charles YP, Al Ansari R, Collinet A et al (2022) Accuracy Assessment of Percutaneous Pedicle Screw Placement Using Cone Beam Computed Tomography with Metal Artifact Reduction [J]. Sensors 22(12):4615
36. Cao B, Yuan B, Xu G et al (2023) A Pilot Human Cadaveric Study on Accuracy of the Augmented Reality Surgical Navigation System for Thoracolumbar Pedicle Screw Insertion Using a New Intraoperative Rapid Registration Method [J]. J Digit Imaging 36(4):1919–1929
37. Burström G, Balicki M, Patriciu A et al (2020) Feasibility and accuracy of a robotic guidance system for navigated spine surgery in a hybrid operating room: a cadaver study [J]. Sci Rep 10(1):7522
38. Yamout T, Orosz LD, Good CR et al (2023) Technological Advances in Spine Surgery: Navigation, Robotics, and Augmented Reality [J]. Orthop Clin North Am 54(2):237–246
39. Gardeck AM, Pu X, Yang Q et al (2020) The effect of simulation training on resident proficiency in thoracolumbar pedicle screw placement using computer-assisted navigation [J]. J Neurosurg Spine 34(1):127–134
40. Iacopino DG, Certo F, Graziano F et al EMG-Guided Percutaneous Placement of Cement-Augmented Pedicle Screws for Osteoporotic Thoracolumbar Burst Fractures; proceedings of the Trends in Reconstructive Neurosurgery, Cham, F 2017//, 2017 [C]. Springer International Publishing
41. Paramasivam Meenakshi Sundaram P, Lai MC, Kaliya-Perumal A-K et al (2024) Overcoming the Learning Curve in Robot-Assisted Spinal Surgery—How Does It Compare to O-Arm Navigation? [J]. Surgeries 5(4):896–907
42. Matinfar S, Salehi M, Suter D et al (2023) Sonification as a reliable alternative to conventional visual surgical navigation [J]. Sci Rep 13(1):5930
43. Lawrie L, Gillies K, Duncan E et al (2022) Barriers and enablers to the effective implementation of robotic assisted surgery [J]. PLoS ONE 17(8):e0273696
44. Benmessaoud C, Kharrazi H, Macdorman KF (2011) Facilitators and barriers to adopting robotic-assisted surgery: contextualizing the unified theory of acceptance and use of technology [J]. PLoS ONE 6(1):e16395
45. Balicki M, Kyne S, Toporek G et al (2020) Design and control of an image-guided robot for spine surgery in a hybrid OR [J]. Int J Med Robot 16(4):e2108
46. Edström E, Burström G, Nachabe R et al (2020) A Novel Augmented-Reality-Based Surgical Navigation System for Spine Surgery in a Hybrid Operating Room: Design, Workflow, and Clinical Applications [J]. Oper Neurosurg 18(5):496–502
47. Barbagallo GM, Certo F, Visocchi M et al (2015) Multilevel mini-open TLIFs and percutaneous pedicle screw fixation: description of a simple technical nuance used to increase intraoperative safety and improve workflow. Tips and tricks and review of the literature [J]. Neurosurg Rev, 38(2):343–54.

48. D'souza M, Gendreau J, Feng A et al (2019) Robotic-Assisted Spine Surgery: History, Efficacy, Cost, And Future Trends [J]. Robot Surg 6:9–23
49. Antonacci CL, Zeng F, Block A et al (2024) Robotic-assisted spine surgery-a narrative review [J]. J Spine Surg 10(2):305–312
50. Ghasem A, Sharma A, Greif DN et al (2018) The Arrival of Robotics in Spine Surgery: A Review of the Literature [J]. Spine (Phila Pa 1976) 43(23):1670–1677
51. Chumnanvej S, Ariyaprakai K, Pillai BM et al (2023) Cost-effectiveness of robotic-assisted spinal surgery: A single-center retrospective study [J]. Laparosc Endoscopic Robotic Surg 6(4):147–153
52. Keric N, Doenitz C, Haj A et al (2017) Evaluation of robot-guided minimally invasive implantation of 2067 pedicle screws [J]. Neurosurg Focus 42(5):E11
53. Khan A, Meyers JE, Siasios I et al (2019) Next-Generation Robotic Spine Surgery: First Report on Feasibility, Safety, and Learning Curve [J]. Oper Neurosurg 17(1):61–69
54. Kochanski RB, Lombardi JM, Laratta JL et al (2019) Image-Guided Navigation and Robotics in Spine Surgery [J]. Neurosurgery 84(6):1179–1189
55. Schwendner M, Ille S, Wostrack M et al (2024) Evaluating a cutting-edge augmented reality-supported navigation system for spinal instrumentation [J]. Eur Spine J 33(1):282–288
56. Liu A, Jin Y, Cottrill E et al (2022) Clinical accuracy and initial experience with augmented reality-assisted pedicle screw placement: the first 205 screws [J]. J Neurosurg Spine 36(3):351–357
57. Edström E, Burström G, Omar A et al (2020) Augmented Reality Surgical Navigation in Spine Surgery to Minimize Staff Radiation Exposure [J]. Spine (Phila Pa 1976) 45(1):E45–E53
58. Von Atzigen M, Liebmann F, Hoch A et al (2022) Marker-free surgical navigation of rod bending using a stereo neural network and augmented reality in spinal fusion [J]. Med Image Anal 77:102365
59. Liebmann F, Von Atzigen M, Stütz D et al (2024) Automatic registration with continuous pose updates for marker-less surgical navigation in spine surgery [J]. Med Image Anal 91:103027
60. Park SM, Kim D, Park J et al (2025) Augmented reality-guided pedicle screw fixation: an experimental study [J]. Asian Spine J 19(6):896–903
61. Tian W, Fan M, Zeng C et al (2020) Telerobotic Spinal Surgery Based on 5G Network: The First 12 Cases [J]. Neurospine 17(1):114–120
62. Rasouli JJ, Shao J, Neifert S et al (2021) Artificial Intelligence and Robotics in Spine Surgery [J]. Global Spine J 11(4):556–564
63. Cho YE (2020) The Future of Spine Surgery in the Fourth Industrial Revolution. Telerobotic Spine Surg [J] Neurospine 17(1):123–124