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Revolutionizing spinal interventions: a systematic review of artificial intelligence technology applications in contemporary surgery

Hao Han[1], Ran Li[1], Dongming Fu[1], Hongyou Zhou[1], Zihao Zhan[1], Yi'ang Wu[1] and Bin Meng[1*]

Abstract

Leveraging its ability to handle large and complex datasets, artificial intelligence can uncover subtle patterns and correlations that human observation may overlook. This is particularly valuable for understanding the intricate dynamics of spinal surgery and its multifaceted impacts on patient prognosis. This review aims to delineate the role of artificial intelligence in spinal surgery. A search of the PubMed database from 1992 to 2023 was conducted using relevant English publications related to the application of artificial intelligence in spinal surgery. The search strategy involved a combination of the following keywords: "Artificial neural network," "deep learning," "artificial intelligence," "spinal," "musculoskeletal," "lumbar," "vertebra," "disc," "cervical," "cord," "stenosis," "procedure," "operation," "surgery," "preoperative," "postoperative," and "operative." A total of 1,182 articles were retrieved. After a careful evaluation of abstracts, 90 articles were found to meet the inclusion criteria for this review. Our review highlights various applications of artificial neural networks in spinal disease management, including (1) assessing surgical indications, (2) assisting in surgical procedures, (3) preoperatively predicting surgical outcomes, and (4) estimating the occurrence of various surgical complications and adverse events. By utilizing these technologies, surgical outcomes can be improved, ultimately enhancing the quality of life for patients.

Keywords Review, Spinal surgery, Artificial Intelligence

Introduction

Spinal surgery, as a significant specialty in the field of medicine, is at a turning point. Thanks to unprecedented medical data and advanced computational technology, medicine is entering a new era of precision healthcare. With the development of the information age, medical data is rapidly accumulating in digital form, injecting powerful momentum into the technological advancement and innovation in the medical field. By combining massive and diverse medical data with efficient computational methods, we are harnessing the potential of artificial intelligence (AI) to accelerate progress in the field of spinal surgery [1, 2].

AI is a potent tool in today's technological landscape, significantly enhancing the accuracy of prediction, prognosis, diagnosis, and biomechanical evaluation of spinal diseases [1]. Compared to traditional statistical methods, AI not only demonstrates superior capabilities but also holds tremendous promise in the medical domain. With the continuous advancement of hardware, software, and computational scientific technologies, AI is poised

*Correspondence:
Bin Meng
mengbinspine@163.com
[1] Department of Orthopedics, The First Affiliated Hospital of Soochow University, Suzhou, China

to gain broader recognition and application in the near future.

However, we have not yet achieved fully automated intelligence. Nevertheless, we have made significant strides, being able to develop systems using AI tools that can simulate human intelligence features—learning from extensive data, making decisions, and providing recommendations [3]. Through artificial neural networks and powerful machine learning techniques, we can dynamically learn from data, providing valuable insights for future actions and decisions. AI represents a vast technological domain, and machine learning, as a vital branch of AI, leverages computer algorithms to learn from data and past experiences, constructing intelligent models, contributing to the development and progress of the medical field [2, 4].

AI has made remarkable strides across various medical fields, each benefiting from advancements in machine learning, neural networks, deep learning, and computer vision. In radiology, AI has significantly enhanced the accuracy and efficiency of image interpretation. Machine learning algorithms, particularly convolutional neural networks (CNNs), have been developed to detect anomalies such as tumors, fractures, and other pathologies in imaging studies including X-rays, CT scans, and MRIs [5]. These AI systems can analyze vast amounts of imaging data rapidly, providing radiologists with precise diagnostic insights and reducing the likelihood of human error [6].

AI applications in cardiology have focused on predictive analytics and personalized medicine. Neural networks have been employed to predict the occurrence of cardiovascular events such as heart attacks and strokes by analyzing patient data, including electronic health records (EHRs), imaging, and genetic information. These predictive models assist clinicians in identifying high-risk patients and tailoring preventive strategies accordingly [7]. Furthermore, AI has been used in the interpretation of echocardiograms and electrocardiograms (ECGs), enhancing the detection of cardiac abnormalities and improving patient management [8].

In oncology, AI has revolutionized cancer diagnosis, treatment planning, and prognosis. Deep learning models, especially those based on CNNs, have demonstrated high accuracy in detecting and classifying various types of cancers from histopathological images, radiographs, and genomic data [9]. AI algorithms can identify subtle patterns that may be missed by human observers, leading to earlier and more accurate diagnoses [10]. AI algorithms are used to detect and monitor conditions such as diabetic retinopathy, glaucoma, and age-related macular degeneration through retinal imaging [9, 11]. AI assists pathologists in analyzing biopsy samples, automating the detection of abnormal cells, and providing quantitative assessments of tissue samples [12]. AI triage systems help prioritize patients based on the severity of their conditions, optimizing resource allocation and improving patient outcomes [13]. Table 1 summarizes the applications of artificial intelligence in various medical fields.

In the context of spinal surgery, AI offers solutions to several specific challenges that traditional methods struggle to address. Spinal surgery demands extremely high precision, as millimeter-level errors can lead to severe consequences. Traditional methods often struggle to achieve the desired accuracy within the complex anatomical structures involved. AI, through advanced image recognition and real-time navigation technologies, can significantly enhance surgical precision and reduce human errors. Accurately predicting individual patient outcomes is also challenging with

Table 1 Applications of artificial intelligence in various medical fields

Medical Field	Application	Description
Radiology	Image Interpretation	CNNs detect tumors, fractures in X-rays, CT, MRI
		Rapid data analysis, reduce human error
		Improve image quality
Cardiology	Predictive Analytics & Personalized Medicine	Predict heart attacks, strokes
		Analyze EHR, imaging, genetic data
		Enhance echocardiogram & ECG interpretation
Oncology	Cancer Diagnosis & Treatment Planning	CNNs detect cancer in histopathology, genomic date
		Early diagnosis
		Personalized treatment plans, optimize radiation doses
Ophthalmology	Retinal Imaging	Detect diabetic retinopathy, glaucoma, AMD
Pathology	Biopsy Sample Analysis	Auto-detect abnormal cells
Emergency Medicine	Triage Systems	Prioritize patients based on severity and optimize resource allocation
Dermatology	Skin Image Analysis	Identify melanoma, other conditions and improve early detection and treatment

traditional methods. AI can analyze vast amounts of historical data, combined with individual patient characteristics, to provide more precise prognostic predictions, aiding doctors and patients in making more informed decisions. Additionally, the complication rate in spinal surgery is relatively high. AI can analyze patient risk factors and surgical technique details to identify potential complication risks and offer personalized prevention strategies, thereby reducing the incidence of complications. Selecting the optimal surgical approach is crucial for the success of the surgery. AI can recommend the best approach based on the patient's specific conditions, such as anatomical variations, lesion locations, and previous surgical history, balancing surgical effectiveness and minimal invasiveness. Therefore, AI demonstrates significant potential in enhancing precision, predicting outcomes, reducing complications, and selecting surgical approaches in spinal surgery.

Additionally, AI offers solutions beyond traditional methods in several key areas. In preoperative planning, AI can generate precise 3D models and simulate different surgical plans, helping doctors choose the best strategy [14]. During surgery, AI-driven augmented reality technologies can provide real-time navigation and visualization of critical structures to surgeons, enhancing intraoperative assistance [15]. Postoperatively, AI can personalize rehabilitation plans and monitor patient recovery in real-time through wearable devices, ensuring tailored and effective rehabilitation [16]. Furthermore, AI systems can learn from each surgery, continuously optimizing algorithms to improve future surgical success rates [17].

To date, there has been no comprehensive review summarizing these developments. This paper aims to explore the full potential of AI technology in driving progress and transformation within the field of spinal surgery. AI not only aids physicians in making more accurate diagnoses and formulating treatment plans but also propels the healthcare system towards becoming more intelligent, efficient, and personalized. We will examine the applications of AI in spinal surgery, discussing its potential benefits, challenges, and future directions. By integrating AI technology with medical practice, our goal is to provide patients with higher quality and more precise medical services, thereby contributing to the advancement of the entire medical field. At this pivotal moment, we foresee AI having a positive impact on the future of spinal surgery, positioning it as a pioneer in the era of precision medicine within the healthcare sector.

Method

Search strategy

A comprehensive search of original articles was conducted through the PubMed search engine to identify the application of Artificial Neural Networks (ANN) in spinal surgery. This review aimed to encompass all full-text publications in English biomedical journals. The following keyword combinations were searched in titles and abstracts: "Artificial neural network," "deep learning," "artificial intelligence," "spinal," "musculoskeletal," "lumbar," "vertebra," "disc," "cervical," "cord," "stenosis," "procedure," "operation," "surgery," "preoperative," "postoperative," and "operative." These keywords were selected as they might be mentioned in the titles or abstracts of relevant articles. A comprehensive search was conducted for the period between 1992 and 2023. The search was carried out in August 2023.

Inclusion and exclusion criteria

All retrieved literature underwent a screening process within the database. Each article was independently reviewed by two reviewers. In case of discrepancies, the article was referred to another reviewer for resolution. Only literature that specifically emphasized relevant research and advancements of AI in spinal disease surgical treatment was included.

Literature related to other diseases, animal studies, and review publications were excluded from consideration. Animal studies were excluded to focus on directly relevant human clinical applications, thereby enhancing the clinical relevance of the study results. Review articles were also excluded to avoid double-counting original studies and ensure our analysis is based on primary data. Only English literature was included, considering the language proficiency of the research team and the fact that most high-impact studies tend to be published in English journals. The time range of 1992 to 2023 was chosen to capture the early applications of artificial neural networks in medical imaging. The search was limited to PubMed due to its comprehensive coverage of biomedical literature.

Data synthesis

Results of all identified studies were summarized in a descriptive table. The table included author names, publication year, treatment stage, study sample, primary mentioned artificial intelligence models, whether compared with traditional non-artificial intelligence models, research focus, and key findings or conclusions. All results were organized in chronological order.

Results

Statistics

The reviewer identified and screened 1,182 articles. After screening, it was determined that 1,082 articles were not relevant. Subsequently, a review was conducted on the remaining 100 articles, and a thorough assessment of eligibility criteria was performed on the full texts. Among these, 5 reviews, 3 animal studies, and 1 retracted article were excluded. Finally, 91 articles were included in this review. The flowchart of the literature review process is illustrated in Fig. 1. AI technology has been applied before, during and after spinal surgery. A summary of all literature is shown in Table 2.

Preoperative

Some literature describes the application of AI in preoperative settings for spinal surgeries. One focus of a study is utilizing AI to assess the suitability of specific surgical techniques for particular spinal disease patients, enhancing patient selection and ensuring safer surgeries through preoperative simulations. Another study utilizes a hybrid AI model, combining data-driven machine learning with expert models to provide surgical recommendations for patients, showcasing the potential of AI to improve surgical decision accuracy. AI further simplifies patient triage for spinal surgeries by integrating questionnaire data and MRI reports, aiming to identify suitable candidates and optimize outpatient efficiency. Machine learning techniques are applied to predict the likelihood of patients undergoing selective lumbar surgeries based on clinical and radiological features, demonstrating hope for improving surgical referrals and healthcare system efficiency. AI-based 3D imaging technologies become valuable tools for evaluating the safety zone of spinal surgeries and understanding variations in relationships between spinal skeletal and neural tissues, highlighting the practicality of AI in enhancing surgical safety. Additionally, utilizing machine learning algorithms to analyze patient data and predict the invasiveness of specific spinal surgeries demonstrates the potential of machine learning in personalized patient care and surgical planning. The document also emphasizes research focused on predicting bone health using machine learning models, particularly in the context of spinal reconstruction surgeries, demonstrating high accuracy in identifying osteoporosis and underscoring the need for further exploration in this field. Collectively, these studies underscore the transformative potential of AI and machine learning in optimizing preoperative preparations for spinal surgeries, ultimately paving the way for wiser and more efficient interventions in spinal surgeries.

Intraoperative

AI has also found widespread applications during surgical procedures. One study focuses on a unique case of a Jehovah's Witness patient refusing the use of blood

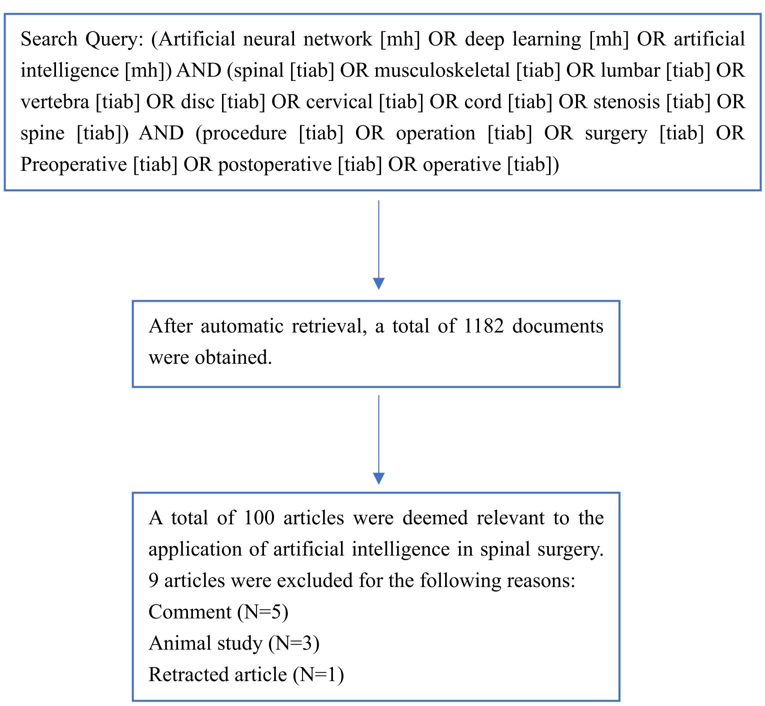

Fig. 1 Flow chart of literature search, review, and selection

Table 2 A list of papers on artificial intelligence used in spinal surgery

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Mert Karabacak et al [18]	2023	Postoperative	Surgery	60%	40%	1.Extreme Gradient Boosted Tree 2.LightGBM 3.CatBoost 4.Random Forest	NO	Predicting short-term postoperative outcomes after cervical spinal fusion surgery using machine learning models	The document concludes that machine learning models effectively predict postoperative outcomes after posterior cervical fusion surgery, aiding risk stratification and personalized patient care. The study highlights the potential of incorporating machine learning into clinical settings for improved prognosis and risk management
Christine Park et al [19]	2023	Postoperative	Surgery	80%	20%	1.Logistic Regression 2.Support Vector Machine 3.Decision Tree 4.Extra Trees 5.Random Forest 6.Gaussian Naïve Bayes 7.k-Nearest Neighbors 8.Multilayer Perceptron 9.Extreme Gradient Boosted Tree	NO	Exploring the application of machine learning algorithms in predicting the minimal clinically important difference (MCID) in postoperative neck pain for patients with cervical spondylotic myelopathy	Model selection for predicting MCID in neck pain depends on the characteristics of the dataset and the clinical research question being addressed. Logistic regression consistently demonstrated the highest precision among all the models tested for both short- and long-term follow-ups, making it a powerful model for clinical classification tasks
Shane Shahrestani et al [20]	2023	Postoperative	Surgery	60%	40%	K-nearest neighbors	YES	Predicting the length of hospital stay (LOS) in patients undergoing spinal surgery for degenerative spondylolisthesis	Machine learning proved to be effective in predicting increased inpatient LOS after spinal surgery for degenerative spondylolisthesis
Katsuhisa Yamada et al [21]	2023	Preoperative	Surgery	-	-	Not mentioned	NO	Using AI-driven 3D imaging to simulate and plan endoscopic lumbar discectomy at the L5-S1 level	Preoperative simulation using 3D MRI/CT fusion imaging is beneficial for determining the feasibility of endoscopic surgery for L5-S1 disc herniation. It affirms the potential of 3D surgery simulation in assessing the anatomical location and insertion angle for successful full-endoscopic surgery
Andrew Cabrera et al [22]	2023	Postoperative	Surgery	80%	20%	1.Random Forest 2.Gradient Boosting 3.Naive Bayes 4.Decision Tree 5.Support Vector Machine 6.k-Nearest Neighbors 7.AdaBoost 8.Multilayer Perceptron	NO	Predicting discharge destinations after elective lumbar fusion surgery by considering age as a factor	The study concludes that machine learning algorithms can effectively predict NHD and presents variables predictive of NHD based on age groups

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Rushmin Khazanchi et al [23]	2023	Postoperative	Surgery	80%	20%	1.Elastic-Net Penalized Logistic Regression 2.Neural Network 3.Random Forest 4.Extreme Gradient Boosted Tree	NO	Predicting postoperative outcomes following Anterior Cervical Discectomy and Fusion (ACDF) using machine learning and deep learning algorithms	The study developed machine learning algorithms that are predictive of readmission, LOS, and nonhome discharge and emphasizes the importance of validation and further research in this domain. BRF showed the greatest predictive ability across all outcomes
Eric A. Geng et al [24]	2023	Postoperative	Surgery	-	-	Random Forest	NO	Predicting nonhome discharge (NHD) after elective ACDF surgery using interpretable machine learning methods	The study validated an explainable machine learning model for predicting nonhome discharge after elective ACDF using common preoperative variables, and emphasized the potential of machine learning to aid surgeons in better facilitating or avoiding postacute care, ultimately contributing to improved patient outcomes
Mitchell S. Fourman et al [25]	2023	Postoperative	Surgery	-	-	Machine learning(Cluster analysis)	NO	Analyzing the risk factors and outcomes associated with surgery for spinal metastatic breast cancer patients	The cluster analysis revealed different patient groups with varying outcomes after open spine surgery for metastatic breast cancer
Andrew Cabrera et al [26]	2022	Postoperative	Surgery	-	-	Random Forest	NO	Exploring the application of a machine learning model, specifically the Random Forest algorithm, to predict outcomes following elective Posterior Cervical Decompression and Fusion (PCDF)	The Random Forest algorithm demonstrated a high degree of predictive accuracy for the examined outcomes. The study emphasizes the potential clinical utility of the predictive analysis in assessing risks during the perioperative period and making informed decisions in the context of elective PCDF
Sara Denn et al [27]	2022	Intraoperative	Anesthesia	-	-	A machine learning monitoring tool	NO	A unique medical case involving a Jehovah's Witness patient who refused blood products during major spinal surgery	The HPI-based treatment algorithm is highlighted as a useful application for complex anesthesia and perioperative patient blood management. The HPI-guided approach provided a high degree of hemodynamic stability while minimizing the risk of dilutional anemia

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Hung-Kuan Yen et al [28]	2022	Postoperative	Surgery	73%	27%	1.Random Forest 2.Xtreme Gradient Boosting 3.Neural Network 4.Support Vector Machine	NO	Enhancing the reproducibility and applicability of machine learning-based clinical prediction models in the context of spine surgery	The study compared random splitting and temporal splitting methods for training and validating predictive models using machine learning algorithms in patients with spinal metastasis, finding that temporal splitting may better capture evolving medical trends, improving predictive accuracy
Albert T. Anastasio et al [29]	2022	Postoperative	Surgery	-	-	Artificial neural network	NO	Identifying optimal combinations of biologic factors to enhance bone healing	The ANN was used to identify combinations of orthobiologic factors that were predicted to be effective in promoting bone healing. Factors like BMP2, BMP7, and OG were identified as crucial in effective combinations
Yong Shen et al [30]	2022	Preoperative	Surgery	80%	20%	Random forest	NO	Leveraging machine learning to predict preoperative bone health status in patients undergoing spinal reconstruction surgery	The study highlights the potential of machine learning in assessing bone health, offers a predictive model with strong performance, and emphasizes the importance of integrating machine learning into clinical practice to enhance bone health screening and surgical planning for spinal reconstructive surgery
Anirudh K. Gowd et al [31]	2022	Postoperative	Surgery	80%	20%	1.Logistic Regression 2.Random Forest 3.Naïve Bayes 4.Decision Tree 5.Gradient Boosting Trees	NO	Utilizing machine learning to predict the hospitalization costs after ACDF spinal surgery	the document highlights the potential of machine learning algorithms to improve cost prediction in healthcare for ACDF procedures
Yu Zhang et al [32]	2022	Postoperative	Surgery	80%	20%	eXtreme Gradient Boosting	NO	Identify the risk factors associated with POD and develop a predictive model to assist clinicians in early intervention	The developed machine learning model, particularly XGBoost, demonstrated strong predictive capabilities for identifying patients at risk of developing POD after surgery for degenerative spinal diseases. The model provides a tool for early screening and intervention for high-risk patients, potentially improving postoperative outcomes and reducing healthcare costs

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Anirudh K. Gowd et al [33]	2022	Postoperative	Surgery	80%	20%	1.Logistic regression 2.Gradient boosting trees 3.Random forest 4.Decision tree	YES	Assessing the feasibility and effectiveness of using machine learning algorithms to predict postoperative adverse events in ACDF patients	Machine learning algorithms modeled the development of postoperative adverse events with superior accuracy to that of comorbidity indices and may guide preoperative clinical decision making before ACDF
Chuang Xiong et al [34]	2022	Postoperative	Surgery	50%	50%	1.Boosted Classification Trees 2.SMOTE + Boosted Classification Trees 3.Boosted Logistic Regression 4.SMOTE + Boosted Logistic Regression 5.Extreme Gradient Boosting 6.SMOTE + Extreme Gradient Boosting 7.Stochastic Gradient Boosting 8.SMOTE + Stochastic Gradient Boosting 9.Generalized Linear Model 10.SMOTE + Generalized Linear Model 11.AdaBoost Classification Trees 12.SMOTE + AdaBoost Classification Trees 13.Random Forest	NO	The development and validation of a predictive model for surgical site infection after posterior lumbar interbody fusion (PLIF) using machine learning techniques	The predictive model developed in this study, using machine learning and SMOTE, can effectively identify patients at high risk for surgical site infection after PILF and help clinicians make informed decisions to reduce infection risk and improve patient outcomes
Sehan Park et al [35]	2022	Postoperative	Surgery	70%	30%	Convolutional Neural Network	NO	Developing a Convolutional Neural Network (CNN) based Deep Learning (DL) algorithm to assess fusion after ACDF	The study successfully developed a CNN-based DL algorithm for fusion assessment after ACDF using lateral cervical spine radiographs. The CNN algorithm demonstrated a high accuracy rate and is expected to aid in detecting pseudarthrosis, assisting surgeons in decision-making without additional cost and radiation exposure
Aditya V. Karhade et al [36]	2022	Postoperative	Surgery	70%	30%	1.Stochastic Gradient Boosting 2.Random Forest 3.Support Vector Machine 4.Neural Network 5.Elastic-net Penalized Logistic Regression	NO	Developing and validating a predictive algorithm for 6-week mortality in patients with spinal metastatic tumors	The algorithm showed good predictive performance, as indicated by high area under the receiver operating curve (AUC) values, both in internal training sets and in independent testing and external validation sets. The study emphasizes the importance of accurate estimation of systemic disease burden to aid in treatment planning and shared decision-making for patients with spinal metastasis

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Aly A. Valliani et al [37]	2022	Postoperative	Surgery	75%	25%	Gradient-Boosted Decision Tree	NO	Predicting prolonged hospital stays after cervical spine surgery	Application of the machine learning model is highlighted for guiding enhanced recovery after surgery protocols, appropriate patient selection, resource allocation, and optimization of management practices to reduce LOS and healthcare costs
D. Müller et al [38]	2022	Postoperative	Surgery	80%	20%	1.Logistic Regression 2.Random Forest 3.Gradient Boosting 4.Lasso Regression 5.Ridge Regression 6.Elastic Net Regression 7.Support Vector Machines 8.Decision Trees 9.K-Nearest Neighbors 10.Artificial Neural Networks 11.XGBoost 12.LightGBM 13.Elastic Net Lasso 14.Recursive Feature Elimination	YES	Utilizing machine learning techniques to predict outcomes in patients undergoing surgery for degenerative spine diseases	The authors emphasized the use of various AI models, including logistic regression, random forest, gradient boosting, and others, to create predictive tools. These predictive models aim to forecast a range of post-surgical outcomes, including pain reduction and functional improvement
Raphael Mourad et al [39]	2022	Preoperative	Surgery	70%	30%	a hybrid model that combines a data-driven machine learning model (random forest) and an expert model (a Bayesian network)	YES	The development and evaluation of a hybrid AI model to predict surgical recommendations for lumbar spinal stenosis (LSS)	AI can bring efficiency and automation to the decision-making process for determining surgical candidacy for LSS, with comparable performance to physicians
Mitsuru Yagi et al [40]	2022	Postoperative	Surgery	70%	30%	1.generalized linear regression model 2.generalized linear mixed model 3.linear regression 4.linear support vector machines 5.single-layer artificial neural networks 6.random trees 7.linear-AS 8.tree-AS 9.extreme gradient boosting linear 10.XGBoost 11.chisquared automatic interaction detection 12.classification and regression tree	NO	Developing a predictive model for clinical outcomes following decompression surgery for LSS	The document concludes that the developed machine learning model offers a valuable tool for surgeons to predict postoperative outcomes for patients undergoing decompression surgery for LSS. The model can help identify patients most likely to benefit from the surgery

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Aly A. Valliani et al [41]	2022	Postoperative	Surgery	75%	25%	decision tree models	YES	Using machine learning to predict non-home discharges in patients who have undergone thoracolumbar spine surgery	The document highlights the potential of machine learning in predicting discharge disposition after thoracolumbar spine surgery, offering insights that could enhance patient care and resource allocation
Mohd Redzuan Jamaludin et al [42]	2022	Postoperative	Surgery	70%or80%	30%or20%	1.Fine K-Nearest Neighbors 2.Weighted K-Nearest Neighbors 3.Ensemble Subspace K-Nearest Neighbors 4.Ensemble Bagged Trees 5.Support Vector Machine 6.Fine Gaussian	YES	The application of machine learning to predict positive functional outcomes in patients undergoing lower lumbar decompression surgeries using transcranial electrical motor evoked potentials (TcMEP) signals	The machine learning models, particularly Fine KNN, achieved high sensitivity percentages in identifying positive functional outcomes based on TcMEP responses. Predicting positive outcomes intraoperatively can aid surgeons in deciding the appropriate depth of decompression during lower lumbar surgeries
Moritz Scherer et al [43]	2022	Intraoperative	Surgery	85%	15%	Convolutional Neural Network	TES	The development and validation of an automated planning tool for lumbosacral pedicle screws using Convolutional Neural Networks (CNNs)	The automated planning tool has the potential to expedite the surgical workflow, provide accurate screw propositions for surgeon confirmation or adjustment, and improve screw stability by optimizing positioning considering local bone quality and anatomical constraints
Samuel S. Rudisill et al [44]	2022	Postoperative	Surgery	80%	20%	1.Decision trees 2.Random forests 3.Artificial neural networks 4.Support vector machines 5.K-nearest neighbors 6.XGBoost	YES	Using AI for predicting early adjacent segment degeneration (ASD) after ACDF surgery	AI models, such as XGBoost and others, have the potential to improve the prediction of ASD after ACDF surgery
Nitin Agarwal et al [45]	2022	Intraoperative	Anesthesia	-	-	1.random forests 2.recursive partitioning	NO	Optimizing the management of blood pressure during spinal cord injury (SCI) surgeries to improve neurological outcomes	The study underscores the importance of careful blood pressure management during surgery for acute SCI patients, utilizing data-driven insights and machine learning to optimize outcomes and reduce complications
Samuel E. Broida et al [46]	2022	Preoperative	Surgery	80%	20%	Deep learning	NO	Identifying suitable candidates for spine surgery using AI-based predictive models, reducing unnecessary consultations and enhancing outpatient clinic efficiency	The study demonstrates the potential of machine learning models to enhance the triage process for spine surgery candidates
Wen-Cai Liu et al [47]	2022	Postoperative	Surgery	70%	30%	1.Logistic Regression 2.Multilayer Perceptron 3.Decision Tree 4.Random Forest 5.Gradient Boosting Machine 6.Xgboost	NO	The prediction of surgical site infection (SSI) risk following lumbar spinal surgery	The developed model can help surgeons identify high-risk patients and reduce SSI incidence

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Shengtao Dong et al [48]	2022	Postoperative	Surgery	-	-	Support Vector Machine	NO	Identifying predictive factors for adverse clinical outcomes following lumbar interbody fusion (LIF) surgery in patients with degenerative lumbar spondylolisthesis (DLS) using machine learning techniques	Both TLIF and PLIF are considered practicable strategies to improve symptoms in patients with degenerative lumbar spondylolisthesis. Postoperative disc height (DH), facet angle (FA), and preoperative local lumbar lordosis (LLS) were statistically associated with short-term clinical outcomes
Hung-Kuan Yen et al [49]	2022	Postoperative	Anesthesia	80%	20%	Skeletal Oncology Research Group (SORG) machine-learning algorith	NO	Predicting long-term opioid prescriptions after lumbar disc herniation (LDH) surgery	The SORG algorithm's successful development and validation offer potential clinical implications, allowing clinicians to identify high-risk patients for prolonged opioid use post-surgery. This enables tailored preventive strategies and interventions to mitigate the risk of opioid dependence
Nicole D. Agaronnik et al [50]	2022	Intraoperative	Surgery	80%	20%	Natural language processing	YES	Developing an automated system to identify and characterize neuromonitoring documentation in electronic health records (EHRs) to aid in quality improvement efforts and patient safety	NLP can be a valuable tool for retrospective identification of operative reports containing neuromonitoring documentation. This approach can facilitate quality improvement efforts focused on exploring factors associated with post-operative neurological deficits and improving patient safety
Nathan Xie et al [51]	2022	Preoperative	Surgery	80%	20%	Artificial Neural Network	YES	Utilizing machine learning to predict surgical candidacy for elective lumbar spine procedures based on clinical and imaging features, aiming to enhance decision-making in surgical planning	The study concluded that accurate modeling of surgical decision-making in lumbar spine surgery using machine learning is possible and could be useful in pre-operative referral and assessment, especially in health systems with limited resources
Soo Heon Kim et al [52]	2022	Postoperative	Surgery	80%	20%	1.Decision Tree 2.Random Forest 3.Artificial Neural Network 4.Support Vector Machine 5.Gradient Boosting Machine 6.Adaptive Reinforcement Learning	NO	The application of machine learning in predicting C5 palsy, a complication that can occur after cervical spine surgery for ossification of the posterior longitudinal ligament (OPLL)	The performance was evaluated using the AUC values, and it was found that machine learning models generally outperformed Logistic Regression in predicting postoperative C5 palsy

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Wenle Li et al [53]	2022	Intraoperative	Surgery	-	-	1.Logistic Regression 2.Multilayer Perceptron 3.Decision Tree 4.Random Forest 5.Gradient Boosting Machine 6.Extreme Gradient Boosting	NO	The application of machine learning in predicting bone cement leakage during percutaneous vertebroplasty, a common procedure for treating osteoporotic fractures of the thoracolumbar spine	The Random Forest algorithm was deemed accurate, simple to use, and demonstrated superior predictive power. The web calculator based on this model can effectively prevent complications after percutaneous vertebroplasty and aid doctors in making informed surgical decisions
Caroline M. W. Goedmakers et al [54]	2022	Postoperative	Surgery	60%	40%	Convolutional neural network	NO	Predicting adjacent segment disease (ASD) in patients undergoing cervical spine surgery using deep learning algorithms	The deep learning algorithm, based on the ResNet50 model, demonstrated good discriminative ability with high accuracy, sensitivity, and specificity in predicting ASD using preoperative cervical MRI
>Ken Porche et al [55]	2022	Postoperative	Surgery	65%	35%	Neural Network Model	YES	Predicting postoperative urinary retention (POUR) in patients undergoing lumbar surgery	The document concludes that both models, logistic regression and the neural network, are useful in predicting POUR after lumbar spine surgery. The logistic regression model showed slightly better predictive performance compared to the neural network model. The combined model achieved improved specificity and NPV compared to individual models, indicating potential benefits of model combination for predictive accuracy
Aditya V. Karhade et al [56]	2022	Postoperative	Surgery	83%	17%	Natural Language Processing	NO	Using natural language processing (NLP) to predict unplanned readmission within 90 days after lumbar spine fusion surgery	The use of NLP algorithms for predictive analysis on free-text documentation shows promise in identifying patients at risk for 90-day readmission following lumbar spine fusion surgery. Integration of NLP applications into healthcare policies may minimize the risk of bias against surgical candidates with higher medical complexity
Qian Li et al [57]	2021	Intraoperative	Surgery	-	-	SegRe-Net	NO	The application of artificial intelligence, particularly neural networks, in the precise segmentation of vertebrae, specifically the laminae, from medical images for robot-assisted laminectomy surgery	The document underscores the significance of AI-driven precise segmentation for robot-assisted laminectomy, presenting SegRe-Net as a promising solution, and calls for further research and validation to enhance clinical effectiveness

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Feng Gao et al [58]	2021	Intraoperative	Surgery	-	-	Residual Neural Network	NO	The application of a deep learning-based denoising algorithm for MRI images in the context of lumbar disc herniation (LDH) diagnosis	It revealed a positive correlation between lumbar disc degeneration and LFJ degeneration, with LFJ asymmetry positively impacting LDH occurrence. The study also noted a higher prevalence of postoperative residual neurological symptoms in LDH patients aged 61–70 years
John T. Schwartz et al [59]	2021	Preoperative	Surgery	68%	32%	Convolutional Neural Network	NO	The development and validation of a machine learning algorithm for identifying ACDF plates using smartphone images of cervical spine radiographs	The study suggested that deploying this algorithm as a smartphone application could be an effective assistive tool for the identification of ACDF plates from radiographic images, potentially improving preoperative planning in revision cervical spine surgery
Katsuhisa Yamada et al [60]	2021	Preoperative	Surgery	90%	10%	-	NO	The research utilized AI-based software to extract lumbar nerve roots from MRI and merge them with CT images	The study demonstrated the utility of AI-based 3D lumbar spine/nerve images for evaluating the bone and nerve relationship in Kambin's triangle, aiding surgical safety and planning
Garrett K. Harada et al [61]	2021	Postoperative	Surgery	80%	20%	XGBoost	NO	Identifying risk factors associated with recurrent disc herniation following initial surgery	The researchers developed a risk calculator known as the RAD Profile, which utilizes machine learning techniques, particularly the XGBoost algorithm, to assess various patient-related factors and provide personalized risk assessments for reherniation
Akash A. Shah et al [62]	2021	Postoperative	Surgery	80%	20%	1.XGBoost 2.Logistic Regression 3.Gradient Boosting 4.AdaBoost 5.Random Forest	YES	Predicting major complications and readmissions following lumbar fusion surgery using machine learning techniques	The study reported a machine learning algorithm for prediction of major complications and readmission after lumbar fusion that outperforms logistic regression. This tool may identify and address potentially modifiable risk factors and decrease complication rates

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Satoshi Maki et al [63]	2021	Postoperative	Surgery	-	-	1.XGBoost: 2.LightGBM 3.Random Forests 4.Elastic Net Regression	NO	Predicting surgical outcomes in patients with cervical Ossification of the Posterior Longitudinal Ligament (OPLL) using Machine Learning (ML) approaches	ML-based models can assist in predicting surgical outcomes and stratifying surgical prognosis for patients with OPLL based on demographic data and pre-operative clinical assessments. Identifying essential preoperative predictors using ML algorithms can provide valuable insights for personalized treatment strategies and improve the overall understanding of surgical outcomes
Bayard Wilson et al [64]	2021	Preoperative	Surgery	40%	50%	deep U-Net machine learning	YES	Developing a machine learning model to identify patients suitable for spine surgery consultation solely using lumbar MRI scans	This study illustrates that automated deep learning models utilizing MRI data to predict surgical candidacy can serve as valuable tools for general practitioners when considering referrals to spinal surgeons for evaluation, potentially optimizing the referral process
Saba Pasha et al [65]	2021	Postoperative	Surgery	80%	20%	Random forest	YES	Predicting surgical outcomes in adolescent idiopathic scoliosis (AIS) using machine learning	The paper highlights the potential of the random forest model in predicting surgical outcomes for adolescent idiopathic scoliosis surgery based on various patient-specific and surgeon-related parameters
Akash A. Shah et al [66]	2021	Postoperative	Surgery	-	-	Skeletal Oncology Research Group (SORG) machine-learning algorith	YES	Patients with spinal metastatic disease, aiming to create accurate predictive models for survival outcomes	The literature reports the successful external validation of the SORG algorithm for preoperative risk prediction of 90-day and 1-year mortality after spinal metastasis surgery
Eren O. Kuris et al [67]	2021	Postoperative	Surgery	-	-	Neural networks	NO	Identifying risk factors and developing predictive models for post-surgery readmission to hospitals following lumbar fusion surgeries	The study highlights that machine learning algorithms, particularly neural networks, can aid in identifying patients at risk of readmission before surgery, which is crucial for better healthcare management and potentially reducing healthcare expenditures
Esther R. Janssen et al [68]	2021	Postoperative	Surgery	-	-	Random forest	YES	The study focuses on adult patients undergoing LSF and aims to identify the impact of physical performance on inpatient functional recovery, length of hospital stay, and pain reduction 1–2 years post-surgery	Better preoperative physical performance is associated with improved short- and long-term outcomes after LSF. Aerobic capacity, back muscle strength, and flexibility were found to be significant predictors

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Peng Cui et al [69]	2021	Intraoperative	Surgery	80%	20%	Convolutional Neural Network	NO	Investigating the use of AI models, particularly CNNs, to accurately identify these critical tissues during surgery, aiming to enhance surgical precision	The integration of AI, particularly CADS, in spinal endoscopic surgery was seen as a potential means to reduce the workload of spinal endoscopists, optimize the learning curve for general surgeons, and enhance overall surgical performance
Jiun-Jen Yang et al [70]	2021	Postoperative	Surgery	-	-	Skeletal Oncology Research Group (SORG) machine-learning algorith	NO	The study focused on the external validation of the SORG ML algorithms for predicting the 90-day and 1-year survival of patients with spinal metastases in a Taiwanese population	The SORG ML algorithms have the potential to improve decision-making by accurately predicting survival rates, aiding physicians and healthcare providers in making appropriate and personalized treatment choices
Hee-Seok Yang et al [71]	2021	Preoperative	Surgery	-	-	1.Standard Deep Learning Model 2.Google AutoML 3.Apple Create ML	NO	The application of deep learning in identifying spinal implants, particularly pedicle screw implants	The study concluded that the application of deep learning, particularly in identifying previous surgical implants, is useful
Kevin Y. Wang et al [72]	2021	Preoperative	Surgery	70%	30%	Artificial Neural Network	YES	Improving the identification of patients suitable for outpatient ACDF, a surgical procedure for neck conditions	The document concludes that predictive analytics and machine learning models can assist in identifying patients appropriate for outpatient ACDF, potentially contributing to better clinical decision-making and cost-effective healthcare
Omar Khan et al [73]	2021	Postoperative	Surgery	80%	20%	1.Boosted logistic regression 2.Support Vector Machine 3.Naïve Bayes 4.Generalized Boosted Machines 5.Partial Least Squares 6.Logistic Regression	YES	Predicting functional decline in patients with degenerative cervical myelopathy post-surgery	The SVM model identified several key predictors of functional decline after surgical decompression for degenerative cervical myelopathy. The machine learning algorithms were found valuable in identifying patients at risk of functional decline post-surgery
Michael L. Martini et al [74]	2021	Postoperative	Surgery	75%	25%	Machine learning	NO	Understanding complex interactions between various predictive features that affect the length of hospitalization, utilizing a novel game-theory-based approach and explainable machine learning methods	The study represents the first to apply novel methods in explainable machine learning to characterize factors influencing prolonged LOS after elective spine surgery

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Andrew K. Chan et al [75]	2021	Postoperative	Surgery	80%	20%	Gradient Boosting Classifier and Gradient Boosting Regressor	NO	Investigating the impact of the medical malpractice environment on the outcomes of spinal fusion surgeries in the United States	Machine learning models (Gradient Boosting Classifier and Gradient Boosting Regressor) were used to predict outcomes related to spinal fusion surgery with reasonable accuracy. These models could aid in preoperative decision-making, resource allocation, and reimbursement
André Wirries et al [76]	2020	Preoperative	Surgery	71%	29%	Deep learning	NO	Predicting therapy outcomes for patients with lumbar disc herniation	The study concluded that their supervised artificial intelligence approach, specifically the deep learning version, could improve the predictability of therapy outcomes for patients with lumbar disc herniation
Arnold Y. L. Wong et al [77]	2020	Postoperative	Surgery	-	-	Support Vector Machine	NO	Predicting early onset adjacent segment degeneration (ASD) in patients undergoing ACDF surgery	The research results indicate that deep paraspinal neck muscle characteristics are predictors for early onset ASD following ACDF, and emphasize the importance of these muscle features in clinical considerations
Andrea Campagnera et al [78]	2020	Preoperative	Surgery	-	-	1.Random Forest 2.Ordinal Ridge Regression	NO	The research aimed to develop a model for quantifying and predicting the invasiveness of lumbar interbody fusion (LIF) surgeries based on inflammatory profiles of individual patients	The study indicates that machine learning can provide decision support for evaluating trade-offs between invasiveness and effectiveness of different treatment options for lower back pain. The ultimate goal is to choose alternative procedures based on each patient's specifics, aligning with the principles of personalized medicine and value-based healthcare
Wesley M. Durand et al [79]	2020	Preoperative	Surgery	70%	30%	1.Random Forest 2.Elastic Net Regression 3.Logistic Regression4.Support Vector Machine	NO	Aiming to develop a model capable of accurately distinguishing between spinal deformity patients undergoing surgical and non-surgical treatment based solely on baseline radiological and clinical data at the time of enrollment	This study developed models with excellent discrimination (area under the curve > 0.9) between patients receiving operative and nonoperative management, using only baseline enrollment data. Future research can explore the implementation of such models for clinical decision support

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Nida Fatima et al [80]	2020	Postoperative	Surgery	70%	30%	logistic regression and LASSO regression	YES	The development and validation of predictive models to anticipate adverse events (AEs) after lumbar degenerative spondylolisthesis (LDS) surgery	The study utilized machine learning algorithms to develop predictive models for prognosticating 30-day overall adverse events after surgery for LDS. The predictive models showed good performance in terms of discrimination, calibration, and decision analysis
Michiel E.R. Bongers et al [81]	2020	Postoperative	Surgery	-	-	Skeletal Oncology Research Group (SORG) machine-learning algorith	YES	Discussing the external validation of machine learning (ML) algorithms developed by the SORG for predicting 90-day and 1-year mortality in patients with metastatic spine disease	In conclusion, the SORG algorithms for survival in spinal metastatic disease were found to generalize well to a contemporary cohort of patients, showing promising predictive capabilities
Aditya V. Karhade et al [82]	2020	Intraoperative	Surgery	75%	25%	1.Stochastic Gradient Boosting 2.Random Forest 3.Support Vector Machine 4.Neural Network 5.Elastic-net Penalized Logistic Regression	YES	The development of machine learning and natural language processing (NLP) algorithms for predicting and identifying vascular injuries in anterior lumbar spine surgery	This study utilized Natural Language Processing (NLP) algorithms to enhance the identification of patients with intraoperative vascular injury. After a comparative analysis, the researchers found that NLP technology significantly outperformed traditional methods
Benjamin S. Hopkins et al [83]	2020	Postoperative	Surgery	75%	25%	deep neural network and machine learning	YES	Predicting the risk of surgical site infection (SSI) following spinal surgery using AI techniques	The document demonstrates the potential of AI and machine learning in predicting postoperative SSI following spinal surgery, identifies significant predictors of SSI, and suggests the integration of AI into clinical decision-making processes for improved patient outcomes
Aditya V. Karhade et al [84]	2020	Postoperative	Surgery	80%	20%	Extreme Gradient Boosting	YES	The application of Natural Language Processing (NLP) and machine learning in the automated detection of postoperative wound infections after spine surgery	The study concluded that the temporal validation of the NLP algorithm demonstrates a proof-of-concept application for automated detection of adverse events after spine surgery and emphasized the potential of adapting this methodology to other procedures and outcomes in spine surgery to enhance quality and safety reporting, and for clinical outcomes research

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Omar Khan et al [85]	2019	Postoperative	Surgery	75%	25%	1.Generalized Boosted Model 2.Earth Model	YES	Using machine learning (ML) to predict the postoperative health-related quality of life (HRQOL) of patients with mild degenerative cervical myelopathy (DCM)	The document highlights the successful application of ML algorithms to predict outcomes for patients with mild DCM after surgery, offering insights into potential surgical predictors and emphasizing the need for further research and validation
Aditya V. Karhade et al [86]	2019	Postoperative	Anesthesia	80%	20%	1.Random Forest 2.Stochastic Gradient Boosting 3.Neural Network 4.Support Vector Machine 5.Elastic-net Penalized Logistic Regression	YES	Developing a predictive model to identify opioid-naïve patients undergoing lumbar spine surgery who are at risk of prolonged postoperative opioid use	The developed models serve as a clinical decision aid to preoperatively risk-stratify opioid-naive patients undergoing lumbar spine surgery. The aid can be used to identify patients at the highest risk of sustained prescription opioid use, allowing for targeted preoperative interventions
Jaret M. Karnuta et al [87]	2019	Postoperative	Surgery	90%	10%	the Naïve Bayes approach with adaptive boosting	NO	Developing a predictive model for costs, length of stay, and discharge disposition	The study demonstrates that machine-learning models, specifically the Naïve Bayes approach with adaptive boosting, can accurately predict costs, length of stay, and discharge disposition
Aditya V. Karhade et al [88]	2019	Postoperative	Surgery	-	-	Skeletal Oncology Research Group (SORG) machine-learning algorith	YES	Focusing on the external validation of machine learning algorithms developed by the SORG for predicting 90-day and 1-year mortality in patients with spinal metastatic disease	The document concludes that the SORG ML algorithms, following successful external validation, have the potential to aid in predicting survival at key postoperative time-points in patients with spinal metastatic disease
Pierre Auloge et al [89]	2019	Intraoperative	Surgery	-	-	AI-assisted navigation	NO	Evaluating the feasibility and effectiveness of augmented reality (AR) and AI guidance systems during percutaneous vertebroplasty, a procedure for treating vertebral compression fractures (VCFs)	AR/AI-guidance proves to be a feasible and safe technique for accurate navigation during percutaneous vertebroplasty. It offers advantages such as reduced radiation dose compared to standard fluoroscopy
Summer S. Han et al [90]	2019	Postoperative	Surgery	70%	30%	Least Absolute Shrinkage and Selection Operator	YES	Predicting adverse events (AEs) following spine surgery using machine learning methods	The document presents predictive models for AEs after spine surgery, demonstrating their potential for clinical use and their ability to inform risk assessment and patient management
Christopher P. Ames et al [91]	2019	Preoperative	Surgery	-	-	unsupervised AI-based hierarchical clustering	NO	The study utilized unsupervised AI-based hierarchical clustering to classify patients with adult spinal deformity (ASD)	The pattern identification resulting from the novel AI-based ASD classification could help optimize treatment by educating surgeons on treatment patterns that yield optimal improvement with the lowest risk

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Aditya V. Karhade et al [92]	2019	Postoperative	Anesthesia	80%	20%	1.Random Forest 2.Stochastic Gradient Boosting 3.Neural Network 4.Support Vector Machine 5.Elastic-net Penalized Logistic Regression	YES	Predicting prolonged postoperative opioid prescription in patients undergoing lumbar disc herniation surgery	The study highlights the potential of machine learning models to predict prolonged postoperative opioid prescription in patients undergoing lumbar disc herniation surgery, aiding in improved postoperative management and patient care
Alessandro Siccoli et al [93]	2019	Postoperative	Surgery	70%	30%	1.Artificial Neural Networks 2.Random Forest 3. Gradient Boosting Machine 4.Logistic Regression	NO	The study used machine learning models to predict patient-reported outcomes, reoperations, prolonged surgery, and extended length of hospital stay for individuals undergoing decompression surgery for lumbar spinal stenosis (LSS)	The study concluded that using machine learning models for preoperative predictive analytics in LSS surgery is feasible and may enable better-informed patient consent and personalized shared decision-making. Access to individualized preoperative predictive analytics for outcome and treatment risks could represent an advancement in surgical care for LSS patients
Zamir G. Merali et al [94]	2019	Postoperative	Surgery	70%	30%	1.Random Forest 2.Support Vector Machine 3.Logistic Regression 4.Simple Decision Tree 5.Artificial Neural Network	YES	Utilizing machine learning techniques to predict surgical outcomes in patients who have undergone decompression surgery for Degenerative Cervical Myelopathy (DCM)	The study demonstrated the potential of machine learning in predicting surgical outcomes for DCM patients, identifying relevant factors, and showcasing the value of RF models in this predictive task
Paul T. Ogink et al [95]	2019	Postoperative	Surgery	80%	20%	1.Neural Network 2.Support Vector Machine 3.Bayes Point Machine 4.Boosted Decision Tree	YES	The application of machine learning methods in predicting postoperative discharge placement for patients undergoing elective lumbar spinal stenosis surgery	The ML-based prediction tool demonstrated effective forecasting of discharge placement after lumbar spinal stenosis surgery, showcasing both good discrimination and calibration. The methodology employed in this study could be applied to predict discharge placement for other diseases and elective treatments, potentially reducing risks associated with delayed discharges and lowering healthcare costs
Aditya V. Karhade et al [96]	2019	Postoperative	Surgery	80%	20%	Super Generalized Boosting	YES	Predicting 90-day and 1-year mortality in patients with spinal metastatic disease using advanced machine learning techniques	The study highlights the potential of machine learning, specifically the SGB model, in predicting survival outcomes in patients with spinal metastases. Integration of such models into clinical practice has the potential to transform treatment recommendations and shared decision-making for patients with spinal metastases

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Aditya V. Karhade et al [97]	2019	Postoperative	Anesthesia	80%	20%	1.Stochastic Gradient Boosting 2.Random Forest 3.Support Vector Machine 4.Neural Network Penalized 5.Logistic Regression	NO	Predicting sustained opioid prescription after ACDF surgery using machine learning algorithms	The study demonstrates the potential of machine learning algorithms in predicting sustained opioid prescription after ACDF surgery, providing a valuable tool for identifying high-risk patients and optimizing preoperative management
Saisanjana Kalagara et al [98]	2019	Postoperative	Surgery	85%	15%	Gradient Boosting Machine	YES	Predicting hospital readmission rates following laminectomy surgery using AI models	The study suggests that machine learning methods are becoming increasingly relevant in healthcare, presenting potential in risk management, diagnosis, and everyday medical practice
Aditya V. Karhade et al [99]	2019	Postoperative	Surgery	80%	20%	1.Neural Network 2.Support Vector Machine 3.Bayes Point Machine 4.Decision Tree	YES	Developing machine learning algorithms to predict 30-day mortality after surgery for spinal metastatic disease	The study concluded that machine learning algorithms hold promise for predicting postoperative outcomes in spinal oncology and emphasized the potential of integrating these algorithms into clinically useful decision tools. It suggested that as data in oncology continues to grow, learning systems and accessible tools may significantly enhance prognostication and management
Victor E. Staartjes et al [100]	2019	Postoperative	Surgery	60%	40%	deep learning models	YES	Developing a personalized clinical prediction model for patients undergoing lumbar disc herniation surgery	Clinical prediction models have the potential to improve personalized shared decision-making in the context of lumbar disc herniation surgery, providing valuable insights to both physicians and patients regarding the likelihood of improvement post-surgery
Aditya V. Karhade et al [101]	2018	Postoperative	Surgery	80%	20%	1.Boosted Decision Tree 2.Support Vector Machine 3.Bayes Point Machine 4.Neural Network	NO	Developing machine learning algorithms to predict non-routine discharge disposition after elective inpatient surgery for lumbar degenerative disc disorders	This study represents the first machine learning study for preoperative discharge planning in elective lumbar disc surgery, and the developed model could potentially be integrated into electronic health record systems for improved decision support

Table 2 (continued)

Author	Year	Treatment stage	Field	Number of sample size		Model type	Comparison with non-ANN models	Main focus	Results/conclusion(s)
				Training	Validation and test				
Jun S. Kim et al [102]	2018	Postoperative	Surgery	70%	30%	1.Logistic Regression 2.Artificial Neural Network	NO	Predicting postoperative complications in patients undergoing adult spinal deformity surgery using AI models, specifically logistic regression and artificial neural networks (ANNs)	The study emphasized the potential of AI models to guide physicians in decision-making, provide personalized care, and enhance response times in critical settings. The ability of AI models to predict clinical outcomes using multidimensional datasets was highlighted, with potential applications in various clinical data sets with class-imbalance issues
Aditya V. Karhade et al [103]	2018	Postoperative	Surgery	-	-	1.Boosted Decision Tree 2.Support Vector Machine 3.Bayes Point Machine 4.Neural Network	YES	Developing machine learning models for predicting 5-year survival rates in patients with spinal chordoma	The study concluded that machine learning models can be effectively utilized for predicting outcomes in rare pathologies like spinal chordoma, even with small datasets
Jun S. Kim et al [104]	2018	Postoperative	Surgery	70%	30%	1.Logistic Regression 2.Artificial Neural Networks	NO	Predicting complications following posterior lumbar spine fusion surgeries	The study concluded that both LR and ANN are valid methods for predicting postoperative complications following posterior lumbar spine fusion. These machine learning models, especially ANN, were found to be more accurate than the traditional ASA scoring system
Nuno Rui Paulino Pereira et al [105]	2016	Postoperative	Surgery	80%	20%	boosted regression algorithm	YES	Developing an algorithm to predict survival outcomes for patients with metastatic spine disease	The study essentially contributes to enhancing the understanding of factors affecting survival in patients with spine metastases and provides a practical tool, the nomogram, to aid in prognostication and decision-making for clinicians
Monika PAPIĆ et al [106]	2016	Postoperative	Surgery	-	-	1.Decision Trees 2.Support Vector Machines 3.Multilayer Perceptron	NO	Predicting the return to work for patients who have undergone operative treatment for lumbar disc herniation (LDH)	The study highlights the potential of AI-based predictive modeling to aid in identifying patients at risk of prolonged work absence after LDH surgery and tailoring interventions to improve patient outcomes
Haydn Hoffman et al [107]	2016	Postoperative	Surgery	-	-	1.Multivariate Linear Regression 2.Support Vector Regression	NO	Predicting postoperative outcomes for patients with cervical spondylotic myelopathy (CSM)	The study suggests that the application of SVR and MLR models using preoperative data can effectively predict postoperative outcomes for patients with CSM, potentially assisting in optimizing patient selection for surgery
Parisa Azimi et al [108]	2015	Postoperative	Surgery	50%	50%	Artificial Neural Network	YES	The study involved the analysis and prediction of recurrent lumbar disk herniation (LDH) in patients who had undergone surgery for lumbar disk herniation	The study demonstrated that Artificial Neural Networks (ANNs) can effectively predict recurrent LDH prior to the initial or index microdiscectomy surgery

products during spinal surgery, effectively managing intraoperative hypotension using an AI tool called the Hypotension Prediction Index (HPI). Another study emphasizes the application of deep learning and CNN to enhance the accuracy and efficiency of pedicle screw insertion during spinal surgeries. Additionally, research explores the automatic identification of neuro-monitoring documents within Electronic Health Records (EHR) using deep learning models and Natural Language Processing (NLP) techniques, aiding in quality improvement efforts. Accurate segmentation of vertebrae is also a focus, with the aim of reducing surgery time and risks in robot-assisted surgeries. The role of AI in assisting surgeons during Percutaneous Transforaminal Endoscopic Discectomy (PTED) is investigated, highlighting the potential of CNN in tissue recognition and improving surgical accuracy. Another innovative study explores the use of Augmented Reality (AR) and AI-guided systems during percutaneous vertebroplasty, providing precise navigation and reducing radiation exposure. Additionally, machine learning algorithms are utilized to predict bone cement leakage during vertebroplasty, aiding in making informed surgical decisions. Lastly, the integration of machine learning and Natural Language Processing (NLP) is explored to predict and identify vascular injuries during anterior lumbar surgery, demonstrating the potential to enhance surgical quality and safety reporting. Overall, these studies collectively demonstrate the transformative potential of AI and machine learning in improving the surgical processes of spinal surgeries.

Postoperative

Numerous studies highlight the applications of AI in postoperative scenarios related to spinal surgeries. Key areas of focus include predictive models for surgical outcomes, particularly complications and readmission rates. To address the opioid crisis, machine learning aids in predicting long-term opioid use postoperatively. The role of machine learning in predicting resource utilization (including hospital costs and length of stay) and in image recognition of spinal implants is crucial. Furthermore, some researchers use machine learning to predict the survival rates of patients with spinal metastases, achieving significant advancements in validating predictive algorithms. In summary, machine learning demonstrates tremendous potential in predicting postoperative outcomes, with the potential to enhance patient treatment outcomes and efficient resource allocation in spinal surgeries.

Discussion

The application of AI technology in various surgical disciplines is rapidly evolving, bringing revolutionary changes to patient care. AI-assisted methods can reconstruct 3D liver models for virtual hepatectomy, allowing for the analysis of total liver volume, tumor-involved segments, and tumor-free segments [109]. Traditionally, decisions for transplant candidates have heavily relied on subjective assessments, but AI can also aid in making complex liver transplantation decisions [110]. In gastrointestinal surgery, AI plays a crucial role in early cancer detection and predicting lymph node metastasis. Because the diagnostic ability and accuracy of endoscopists for early gastrointestinal cancers vary, AI combined with the expertise of endoscopists can improve the accuracy of early gastrointestinal cancer diagnosis [111]. Additionally, AI can predict lymph node metastasis preoperatively, thereby minimizing the need for additional surgeries after endoscopic resection of colorectal cancer [112]. In breast surgery, AI assists in breast reconstruction and breast cancer screening. In the field of breast reconstruction, AI improves surgical procedures, enhances outcomes, and simplifies decision-making [113]. Additionally, AI aids human experts in breast cancer screening [114]. Predicting individual mortality rates for congenital heart disease patients undergoing cardiac surgery and estimating mortality risk for patients receiving left ventricular assist device therapy are critical applications of AI [115, 116]. Comprehensive preoperative understanding of lung anatomy is crucial for accurate surgical planning and case selection. Identifying intersegmental planes on CT scans is extremely challenging. AI enables the 3D visualization of complex anatomical structures, such as lung segment partitions, vascular branches, and bronchial anatomy, aiding in the preoperative planning of segmental lung resection [117]. In the field of neurosurgery, artificial intelligence can assist in planning surgical pathways using preoperative MRI images [118]. Additionally, it can analyze biopsy samples during surgery to distinguish between healthy tissue and benign or malignant tumor tissue [119]. In urological surgery, AI contributes to the early diagnosis of renal cell carcinoma and predicts recurrence following prostate cancer resection. Using NMR-based serum metabolomics and self-organizing maps, AI can facilitate the early diagnosis of renal cell carcinoma [120]. Additionally, AI can automatically predict early recurrence in patients following robot-assisted prostatectomy [121]. AI technology continues to enhance surgical precision, improve patient outcomes, and facilitate personalized care across these specialized fields. The application of artificial intelligence technology in various surgical fields is partially illustrated in Table 3.

Table 3 Application of artificial intelligence technology in various surgical fields

Surgical Specialty	Application	Description
Hepatobiliary Surgery	Virtual hepatectomy	The use of AI-assisted methods to reconstruct 3D liver models for virtual hepatectomy, including functional liver volume analysis, is reliable for the practical planning of liver tumor resection
	Transplantation decisions	There is cautious optimism about the potential of AI clinical decision support to improve patient clinical and equity outcomes
Gastrointestinal Surgery	Early cancer detection	Employing AI-based endoscopes would enable early cancer detection. The better diagnostic abilities of AI technology may be beneficial in early gastrointestinal cancers in which endoscopists have variable diagnostic abilities and accuracy
	Prediction of lymph node metastasis	Compared with current guidelines, artificial intelligence significantly reduced unnecessary additional surgery after endoscopic resection of T1 CRC without missing LNM positivity
Breast Surgery	Assistance in breast reconstruction surgery	Artificial intelligence can play a key role in advancing breast reconstruction by facilitating preoperative planning, enhancing surgical precision, personalizing reconstruction, and assisting in postoperative care
	Breast cancer screening	Machine learning can integrate hundreds of thousands of image-level, patient-level, and tumor-level variables to develop complex algorithms that have the potential to significantly enhance the accuracy of human breast cancer screening
Cardiothoracic Surgery	Predicting postoperative mortality	The predictive results of the Random Forest model confirm that machine learning algorithms can assist clinical experts, patients, and their families in analyzing the potential risks associated with cardiac surgical interventions
	Risk prediction in patients undergoing LVAD implantation	Machine Learning may play a significant role in risk prediction for Left Ventricular Assist Device (LVAD) therapy, both as a standalone tool and as an adjunct to traditional modeling methods such as Logistic Regression (LR)
	Assisting in segmental pulmonary resection	Virtual Reality and Artificial Intelligence can enable the three-dimensional visualization of complex anatomical structures, including pulmonary segment partitioning, vascular branching, and bronchial anatomy
Neurosurgery	Surgical pathway planning	Algorithms can estimate the precise optimal surgical path that avoids critical brain structures. They calculate the correct incision point on the scalp, then search for different paths to the tumor's initial location, and identify the optimal linear surgical route
	Guiding the extent of tumor resection	Machine learning methods are employed to address the aforementioned issue by automatically distinguishing between healthy tissue and benign/malignant tumor tissue obtained from the resection cavity during tumor surgery. The algorithm operates quickly, functioning within the surgical time frame. It directly outputs whether the sample contains tumor cells
Urological Surgery	Early diagnosis of renal cell carcinoma	The SOM model utilizing serum metabolic markers can accurately predict early RCC diagnosis and can be used to assess postoperative metabolic recovery
	Predicting recurrence after prostate cancer resection	Machine-learning techniques can produce accurate disease predictability better that traditional statistical regression. These tools may prove clinically useful for the automated prediction of patients who develop early biochemical recurrence after robot-assisted prostatectomy

This article provides a comprehensive overview of various research efforts utilizing the power of AI in the field of spinal surgery. These studies aim to develop and validate predictive models related to spinal surgery, aiming to enhance surgical outcomes, predict postoperative complications, and ultimately improve patient prognosis. Researchers employ a range of AI methods to analyze extensive datasets. These models, once trained, can assess surgical indications, assist in the surgical process, and predict preoperative surgical efficacy, postoperative complications, readmission rates, and non-home discharge outcomes. Additionally, most articles emphasize the importance of external validation, with many studies highlighting the necessity of validation using independent datasets. Furthermore, the document advocates for standardized reporting and validation methods, aligning with the broader scientific concern for the repeatability and reliability of AI-based research.

Artificial intelligence has preoperative applications, specifically in identifying surgical indications and detecting pedicle screws from previous spinal surgeries. Several researchers are leveraging AI to determine surgical indications and evaluate patient suitability for spinal surgery. This involves humans augmented by AI [21, 30], decision making guided by AI [39, 72, 79], and fully autonomous AI systems [64]. They also seek to choose appropriate surgical approaches for patients who have already decided on surgery [51, 60]. AI can analyze a large number of cases to identify patient populations suitable for specific types of surgery and predict postoperative outcomes. This helps both doctors and patients make more informed surgical choices, ultimately improving the success rate of surgeries and the quality of life for patients. It also alleviates the burden on doctors, saves time and costs, and enhances the efficiency of healthcare services, allowing more patients to receive timely and personalized medical care. Artificial intelligence and machine learning technologies can evaluate whether patients are suitable for surgical treatment based on imaging examination results and their medical history; however, the final decision still requires clinical judgment by physicians.

Some studies aimed to use deep learning algorithms to accurately identify pedicle screws implanted during spinal surgery based on radiographic images (anterior–posterior and lateral views of the spine) [59, 71]. This could assist clinicians in evaluating previous surgeries, especially revision surgeries. The research compared the performance of different deep learning algorithms, including standard deep neural network models using transfer learning, and two automated platforms: Google Auto ML and Apple Create ML. The evaluation was based on accuracy and recall metrics for identifying the implants. By demonstrating the effectiveness of deep learning in identifying surgical implants, these studies could aid in patient assessment and decision-making during spinal surgery. Some researchers have deployed this algorithm as an accessible smartphone application for further evaluation, improvement, and eventual widespread use, which will serve as a valuable supplement to clinical practice.

Artificial intelligence is utilized intraoperatively to assist and enhance the surgical process during operations. The integration of AI technology into spinal surgery to assist during the surgical process is a prominent research area [27, 43, 45, 50, 57, 82, 89]. It's worth mentioning a particular study that discussed a case in which a patient, due to religious beliefs, declined a blood transfusion. During the spinal surgery, AI and machine learning were employed to implement a fluid-restricted treatment plan. The patient underwent a major spinal surgery, and an innovative monitoring tool called the Hypotension Prediction Index (HPI) was utilized to predict and manage intraoperative hypotension [27]. AI technology provides crucial information for surgical planning by analyzing a vast amount of patient imaging data and considering the patient's anatomical structure and medical condition. It assists in planning surgical pathways, such as screw pathways, and detects intraoperative damage or anomalies, predicting potential issues and challenges in advance. AI also enables real-time analysis of patients' physiological data, surgical images, and monitoring information, providing surgeons with real-time feedback and aiding in decision-making, including adjustments to the use of medications during the surgery. This assistance helps tailor the surgical strategy, minimizing surgical risks to the greatest extent. The application of artificial intelligence can significantly reduce the risks associated with surgery. However, the formulation of surgical strategies should ultimately be decided by clinical physicians.

Artificial intelligence is used postoperatively to predict surgical complications, outcomes, discharge status, hospitalization costs, opioid use, and survival in patients with spinal metastases or tumors. The majority of researchers focus their studies on postoperative complications. These include postoperative pain [19], functional decline [73], the need for blood transfusions after surgery [26], postoperative infections [26, 34, 47, 80, 83, 84], delirium [32], urinary retention [48, 55], post-cervical surgery C5 palsy [52], and even patient mortality after surgery [25, 102, 104]. Some patients may experience neurological symptoms postoperatively, such as swelling, numbness, limp, and weakness of the lower limb [58, 100]. Certain patients may experience extended hospital stays [20, 26, 37, 87], recurrence of symptoms after surgery [44, 54, 61, 77, 108], the need for reoperation [25, 26, 48], readmission after discharge [23, 26, 56, 62, 67, 98], and various other complications and adverse events [90, 91, 102, 104]. Studying these complications can identify potential issues or risk factors, helping physicians understand in advance the risks patients may face. This understanding enables better communication with patients regarding potential risks and postoperative recovery, assisting patients in making informed decisions about whether to undergo surgery. Physicians can also adjust surgical plans based on predictive results, choosing the most suitable treatment path for the patient and taking appropriate measures to minimize potential risks. This information provides a basis for improving medical practices and enhancing patient safety. Most authors believe that AI and machine learning technologies can assist clinicians in decision-making by incorporating relevant risk factors, thereby aiding in the prevention and treatment of various postoperative complications. However, the overall clinical efficacy remains insufficient at present, necessitating further validation and refinement.

In the field of surgical advancements, a group of renowned researchers is turning to the use of machine learning and AI to predict surgical outcomes. By utilizing comprehensive datasets that encompass patient clinical data, imaging data, medical history, and the specific type of surgery conducted, these researchers aim to develop predictive models. This involves humans augmented by AI [35, 44, 46, 63, 76, 91], decision making guided by AI [33, 78, 107], and autonomous AI systems [29, 38, 40, 65, 68, 82, 93, 94]. The goal is to provide a detailed understanding of potential outcomes following spinal surgery. Many spinal surgeries involve relatively significant trauma, and the majority of patients undergoing spinal surgery are elderly. Therefore, predicting surgical outcomes in advance, assessing risks and benefits associated with the surgery, and performing surgery only on patients for whom the benefits outweigh the risks are critical. This approach enhances treatment outcomes and paves the way for wiser and more precise medical interventions. The recovery period after spinal surgery is inherently lengthy, involving a series of complex processes, including rehabilitation, physical therapy, and meticulous follow-ups. Predicting outcomes in advance is also beneficial in preparing healthcare professionals, patients, and their families for postoperative care. This is crucial for a patient's recovery, ensuring a smooth recovery, and overall effectiveness of the surgical intervention. Artificial intelligence and machine learning technologies have demonstrated value in predicting adverse events such as surgical site infections, pneumonia, and more. Some studies suggest that their predictive capabilities surpass those of traditional models. These tools can improve the acquisition and usability of prognostic information in clinical practice. However, their effectiveness and practicality still require further validation. Ultimately, these tools will aid in facilitating decision-making and managing patient expectations.

When a patient is designated as "non-home discharge" upon leaving a medical facility, there is a significant deviation from the traditional post-discharge trajectory. These patients are directed to alternative care facilities or institutions based on their unique medical needs and individual circumstances, rather than returning to their familiar homes. Older patients undergoing spinal fusion surgery are more likely to be discharged to a rehabilitation center. This targeted transition to a non-home environment indeed carries significant financial implications, leading to a notable increase in healthcare insurance expenditures. On the other hand, compared to patients discharged directly home, those sent to non-home environments experience higher rates of postoperative complications, readmissions, and other adverse events. Some forward-thinking researchers are striving to use AI methods to predict postoperative non-home discharge. These AI-driven predictive models are documented in various studies [18, 22–24, 41, 75, 87, 95, 101], aiming to streamline the decision-making process regarding patient discharge. The primary objective of this emerging research is to enable healthcare professionals to accurately predict potential discharge trajectories. By doing so, they can optimize the postoperative transition for each patient, ultimately reducing complications and improving healthcare outcomes. Additionally, by optimizing the allocation of patients to appropriate care settings, these AI-driven predictions can help manage healthcare resources wisely, potentially reducing medical costs without compromising the quality of care. Integrating artificial intelligence into healthcare systems holds the promise of fundamentally transforming patient care and shaping more efficient healthcare approaches for those in need. Researchers employ rigorous methodologies, and the algorithms used demonstrate satisfactory classification performance in predicting patient post-discharge outcomes. However, due to factors such as the patient samples possibly not being fully representative of all patients, and the data not including all specific factors that may be related to the risk of adverse postoperative outcomes, these technologies can only serve as auxiliary tools and cannot completely replace clinical judgment.

The financial aspects of surgery and hospitalization have always been a significant concern for patients. To address this issue, some researchers are focusing on accurately predicting the overall hospitalization costs for surgical patients [31, 75, 87]. This predictive model holds great significance for both patients and healthcare institutions. For healthcare institutions, accurately predicting the overall cost of patients is crucial. It aids in proactive financial planning, budgeting, and effective resource allocation. With precise cost predictions, healthcare organizations can design cost structures in advance, ensuring the sustainability and affordability of healthcare services without compromising quality. Equally important is the impact on patients. Having a clear understanding of the expected costs associated with surgery and its subsequent treatments enables patients to make informed medical decisions. Transparent cost information bridges the knowledge gap, allowing patients to comprehend the financial implications and plan accordingly. It creates a collaborative environment for effective communication and shared decision-making between patients and healthcare professionals. Ultimately, this informed and collaborative approach enhances the efficiency and effectiveness of healthcare resource allocation, aligns patient expectations with the reality of healthcare costs, and fosters a more equitable and patient-centered healthcare system. In the realm of predicting hospitalization and surgical costs, AI and ML technologies not only play a pivotal role in forecasting but also in identifying additional variables that are crucial in determining the cost of care. This further enhances cost efficiency and alleviates financial burdens.

Opioids are a class of potent analgesic medications that work by binding to opioid receptors in the brain, effectively blocking pain signals and relieving moderate to severe pain. While the use of opioids in pain management is highly effective, the inherent risks of addiction, tolerance, and potential side effects necessitate careful monitoring and regulation. Many studies delve into the prescription patterns of opioids after spinal surgery, aiming to investigate the continued use of opioids post-surgery and identify influencing factors [49, 86, 92, 97]. These studies consider key factors such as preoperative opioid use, antidepressant usage, tobacco use, insurance status, and preoperative medication therapies. The ultimate goal is to develop a stratified predictive algorithm for preoperative patients, designed to minimize long-term opioid use through informed decisions and personalized care. Despite advancements in predictive analytics, the application of these medications still necessitates stringent human oversight to ensure safe and effective use.

In the field of spinal care, some literature is dedicated to developing postoperative survival and death prediction models, specifically tailored for patients with spinal metastases or spinal tumors [28, 36, 99, 103, 105]. These predictive models play a crucial role in providing information for clinical decisions regarding surgical interventions and appropriate surgical strategies for patients in this unique medical condition. Decisions regarding surgical interventions for spinal tumors are often based on the estimated life expectancy of the patients, with the overall goal being to maintain or improve their quality of life. The development and implementation of postoperative survival and death prediction models have been instrumental in this regard. These models offer valuable insights into the expected postoperative survival time and the occurrence of potential adverse outcomes for clinical practitioners and healthcare providers. These predictive models fundamentally enhance end-of-life care for patients with spinal metastases or tumors. By anticipating survival trajectories and the likelihood of postoperative adverse events, healthcare professionals can adjust treatment plans accordingly, optimizing the quality of care provided to patients in their remaining time. Moreover, these predictive models enable patients and their families to make informed decisions regarding treatment choices, end-of-life planning, and overall care strategies, forming an approach that is patient-centered and prioritizes individual well-being and comfort. Integrating these predictive models into clinical practice will significantly improve the overall management and outcomes of patients facing challenging spinal health conditions. It is worth mentioning that some researchers have focused on the validation and evaluation of the SORG (Skeletal Oncology Research Group) machine learning algorithm, which is used to predict the 90-day and 1-year mortality of patients with spinal metastatic disease [49, 66, 70, 81, 88]. They conducted validation on an independent population to assess the accuracy and practicality of these algorithms in predicting survival outcomes, especially in the context of spinal metastatic disease. They believe that the SORG machine learning algorithm has the potential to be a valuable tool for predicting survival in spinal metastatic diseases. This algorithm has shown good predictive capability in assessing the 1-year survival rate of patients with spinal metastases and has undergone external validation, confirming its effectiveness in practical applications. This has led to its widespread use in spinal tumor research.

Researchers believe that applying AI technology to spinal surgery can enhance the safety, precision, and efficiency of the surgical process. However, the use of AI in assisting spinal surgery requires caution. Its limitations and risks must be thoroughly considered, and the professional judgment of the surgeon should always remain at the core of decision-making.

Firstly, the quality and representativeness of the data used to train AI models are critical. The performance of these models heavily depends on the diversity and accuracy of the training data. For instance, in tumor diagnosis, if the training data predominantly comes from a specific race or region, the AI's diagnostic accuracy may decrease when applied to other populations. This highlights the risk of bias and reduced efficacy in certain demographic groups or rare cases.

Another challenge is the generalization capability of AI models. These models may struggle to handle scenarios not present in the training data. In complex or rare cases, such as congenital heart anomalies in cardiac surgery, AI's performance may fall short of expectations. Additionally, the interpretability of AI decisions remains a significant hurdle. Many high-performing AI models, like deep learning algorithms, operate as "black boxes," making it difficult to explain their decision-making processes. This lack of transparency can undermine trust among doctors and patients and pose legal and ethical concerns.

For example, in surgical planning, if an AI cannot justify its recommended surgical path, it may be challenging for surgeons to adopt its suggestions.

Real-time performance is another critical limitation. Some sophisticated AI models require substantial computational resources, making real-time processing challenging. In fast-paced surgical environments, this can restrict AI's applicability. For instance, during liver tumor surgery, if the AI cannot update resection plans in real-time, it may hinder surgical flexibility. Additionally, AI faces difficulties in handling unstructured data, such as surgical notes and medical records. This limitation can prevent AI from fully leveraging all available information, potentially impacting its ability to predict postoperative complications accurately.

Adaptability to dynamic environments is another concern. The surgical setting is inherently dynamic, and AI may struggle to adapt to unforeseen situations. In complex surgeries, unexpected events like sudden bleeding may require immediate adjustments that AI might not be able to provide. Ethical and legal issues also pose significant challenges. The use of AI involves complex questions around accountability, informed consent, and patient autonomy. These concerns can impede the widespread adoption of AI in high-risk areas. For example, if an AI-recommended treatment leads to adverse outcomes, determining responsibility can be problematic.

Finally, the continuous updating and maintenance of AI systems are essential but challenging. Medical knowledge and practices evolve rapidly, necessitating regular updates to AI systems to maintain their relevance and accuracy. This requires ongoing investment and expertise, which may be challenging for some healthcare institutions. If AI systems are not updated promptly to incorporate new diagnostic standards or treatment methods, they risk providing outdated recommendations.

Although this review provides a comprehensive overview of the advancements in AI applications in spinal surgery, it is important to acknowledge certain inherent limitations in our study. Our review exclusively includes literature published in English. This choice was made considering the language proficiency of our research team and the fact that most high-impact studies tend to be published in English-language journals. However, we recognize that this may introduce language bias, potentially excluding valuable research published in other languages. Our literature search was confined to PubMed. PubMed was chosen due to its extensive coverage of biomedical literature and its accessibility. However, we acknowledge that this focus might have led to the omission of significant studies, particularly those published in engineering or computer science journals, which are also relevant to the development and application of AI in spinal surgery. Additionally, one notable weakness in the current body of literature is the lack of high-quality neural networks. Although there have been significant advancements, many studies still rely on neural networks that may not be sufficiently robust or generalizable. High-quality neural networks require extensive, diverse datasets and significant computational resources, which are often limited. This limitation affects the reliability and applicability of AI models in clinical practice and should be addressed in future research.

In conclusion, while AI serves as a powerful supplemental tool aimed at enhancing the efficiency and accuracy of surgeons, it is unlikely to replace human surgeons entirely in the foreseeable future. The complex, dynamic nature of surgical procedures and the need for human intuition, real-time judgment, and ethical decision-making underscore the indispensable role of surgeons. Future research and publications should continue to explore these limitations and develop strategies to mitigate them, ensuring that AI technology can be safely and effectively integrated into spinal surgery and other medical fields. Specifically, more research is needed to address current limitations such as data quality, model interpretability, and integration into clinical workflows. Improving the diversity and representativeness of training data can help mitigate biases and enhance AI performance across different patient populations. Enhancing the interpretability of AI models is crucial for gaining the trust of both surgeons and patients, which can be achieved through the development of more transparent algorithms and explainable AI techniques. Integrating AI systems seamlessly into clinical workflows requires collaboration between AI developers and healthcare professionals to create user-friendly interfaces and ensure that AI recommendations can be easily understood and acted upon in real-time. Additionally, future research should focus on variable analysis for approach selection in spinal surgery, which involves identifying the key factors that influence surgical decisions and outcomes. By analyzing these variables, AI can provide more tailored and context-specific recommendations, ultimately improving patient care. Addressing these challenges and advancing AI research will pave the way for its broader adoption and greater impact on clinical practice in spinal surgery and beyond.

Conclusion

In recent years, AI technology has been widely applied in the field of spinal surgery, making significant contributions to the diagnosis, treatment, care of patients, and the development of surgical techniques. Through clever algorithms, doctors should be able to predict various postoperative outcomes before surgery. AI at the current stage is primarily a powerful supplemental tool aimed at enhancing the efficiency and accuracy of surgeons.AI technology can provide significant support in data analysis, surgical planning, intraoperative navigation, and postoperative monitoring, thereby improving patient outcomes and reducing surgical risks. However, we do not believe that AI will completely replace human surgeons in the foreseeable future. Surgical procedures involve many complex and dynamically changing situations, with many decisions relying on the surgeon's experience, intuition, and real-time judgment—factors that current AI technology is challenging to fully replicate. Surgeons are not merely technical executors; they also need to communicate with patients and their families, provide emotional support, and make ethical decisions, aspects that AI cannot replace. In the future, with the continued development of AI technology, more research and publications on its applications in spinal surgery are expected, and further studies will be necessary to explore and advance the field.

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Authors' contributions
H.H. and L.R. were responsible for proposing the topic, designing the research methods, and drafting the initial manuscript. F.D. and Z.H. were responsible for literature retrieval and collection. W.Yi. and Z.Z. were responsible for reviewing the collected literature. Meng Bin was responsible for the topic design, writing, reviewing, and obtaining funding. The final draft was read and approved by all authors.

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Data availability
The data that support the findings of this study are included in this manuscript, and the original files are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Institutional Ethics Committee of Soochow University.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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