Review

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Artificial intelligence and its use in spine surgery and preparation of predictive models: a systematic review

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Abstract

During the last decade, artificial intelligence (AI) has witnessed phenomenal growth, accompanied by unparalleled opportunities in health. The integration of machine learning at the heart of health systems has shaped a revolution that helps to reduce health, social, and economic inequities while improving global health outcomes. The use of AI for spine surgery, in particular, serves to enhance the accuracy of predicted algorithms and can be used to improve surgical accuracy and reduce operative time, thereby enhancing efficiency and productivity. This review outlines the current literature on the use of AI in spine surgery and identifies its established evidence to provide positive surgical outcomes. With all these promises, AI in spine surgery remains in its infancy; it is anticipated that further development will yield much greater benefits in the immediate future.

Keywords: artificial intelligence, spine, surgery

Introduction

An article from Insider magazine read, "Chat GPT-4 passed the US medical licensing exams with flying colors," read a recent Insider article[1]. That is just one among the many strings of accomplishments that the language processing tool has managed to accomplish. However, such events have caused society to consider artificial intelligence's (AI's) role in medicine, especially in complex procedures such as spine surgery. Spine surgery is a term that covers a set or a group of surgical procedures that are meant to correct injuries or deformities to the backbone or spinal cord [2]. Some studies that have been done on the role of AI in spine surgery and predictive models show the potential for increasing accuracy, reducing surgery operation times, and improving its efficiency and effectiveness[3]. This study will review the available literature to identify the common trends and consensus among scholars regarding the role of AI in spine surgery and the preparation of predictive models.

The paper aims to evaluate the current literature on the role of AI in spine surgery, including elaborating on how AI can enhance surgical accuracy, reduce operative times, and improve the overall efficiency and effectiveness of spine surgeries. We tried to identify common trends and consensus among scholars in the application of AI in spinal procedures and assess the development and implementation of predictive models in this field. The paper reviews recent studies to provide a comprehensive understanding of AI's potential impact on spine surgery, with an emphasis on areas where AI can offer the most significant benefits.

The review has an adequate number of advantages and disadvantages. Its principal strength is that it provides an overview of AI in spine surgery, including diverse topics that provide an excellent balance of knowledge related to robotics-assisted surgical techniques, predictive modeling, and image analysis. An emphasis on several topics allows the reader to receive a comprehensive perspective on how AI may affect the field. It also depends on state-of-the-art materials, as it embodies articles of the last 5 years. This will make the current information reviewed and is reflective of the latest developments in AI. In particular, it is of the essence because it is believed that AI is one of the areas in which changes happen fast. Furthermore, the review represents a good balance between theoretical discussions and practical applications, further pinpointing real-world benefits that include enhanced surgical accuracy and reduction in operative time, thereby making findings more amenable to practical use in clinical settings. By mentioning barriers to AI implementation, including poor data quality and infrastructure limitations, the review gives a balanced statement of both the potential and limitations of AI. The clarity and neat structure of the review in the last instance make reading easy, as readers may easily follow the discussion.

However, some limitations have to be considered. First, the number of studies included in the review equals three, which may not fully represent the entirety, yet vast literature concerning AI in spine surgery. This might thus present conclusions that are difficult to generalize. The other drawback has to do with ethical and legal issues, which are highly relevant in light of AI integration into health care. There is also a need to take into account privacy concerns regarding patient data, accountability of artificial intelligence-driven decisions. Perhaps the emphasis on spine surgery, while important in and of itself, could be framed into a greater context of how AI functions in alternative surgical specialties for a greater understanding of the applications available. Since AI in spine surgery is still large in its

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infancy, most of the benefits mentioned herein are potential, not proven, and the long-term impact is hard to clearly read. Moreover, no long-term data outcomes are reviewed, including patient recovery rates and predictive model durabilities that could comprehensively establish the effectiveness of AI over time. This review remains a valuable contribution in spite of these limitations and would have been even more instructive if these areas had been further explored.

Method

A detailed and systematic literature search was conducted using several reputable databases, including the National Center for Biotechnology Information (NCBI), Multidisciplinary Digital Publishing Institute (MDPI), Springer, and ScienceDirect. These databases were selected for their breadth of research on AI and spine surgery. To ensure the transparency and reproducibility of the search process, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed throughout the study selection process (see Fig. 1 – PRISMA flow chart).

Only articles published within the last 5 years were used for the research review. The reason is that AI is still in its infancy and, therefore, undergoing rapid evolution. It is, consequently, likely that information contained within old articles may not reflect the current trends in the industry. The trends keep

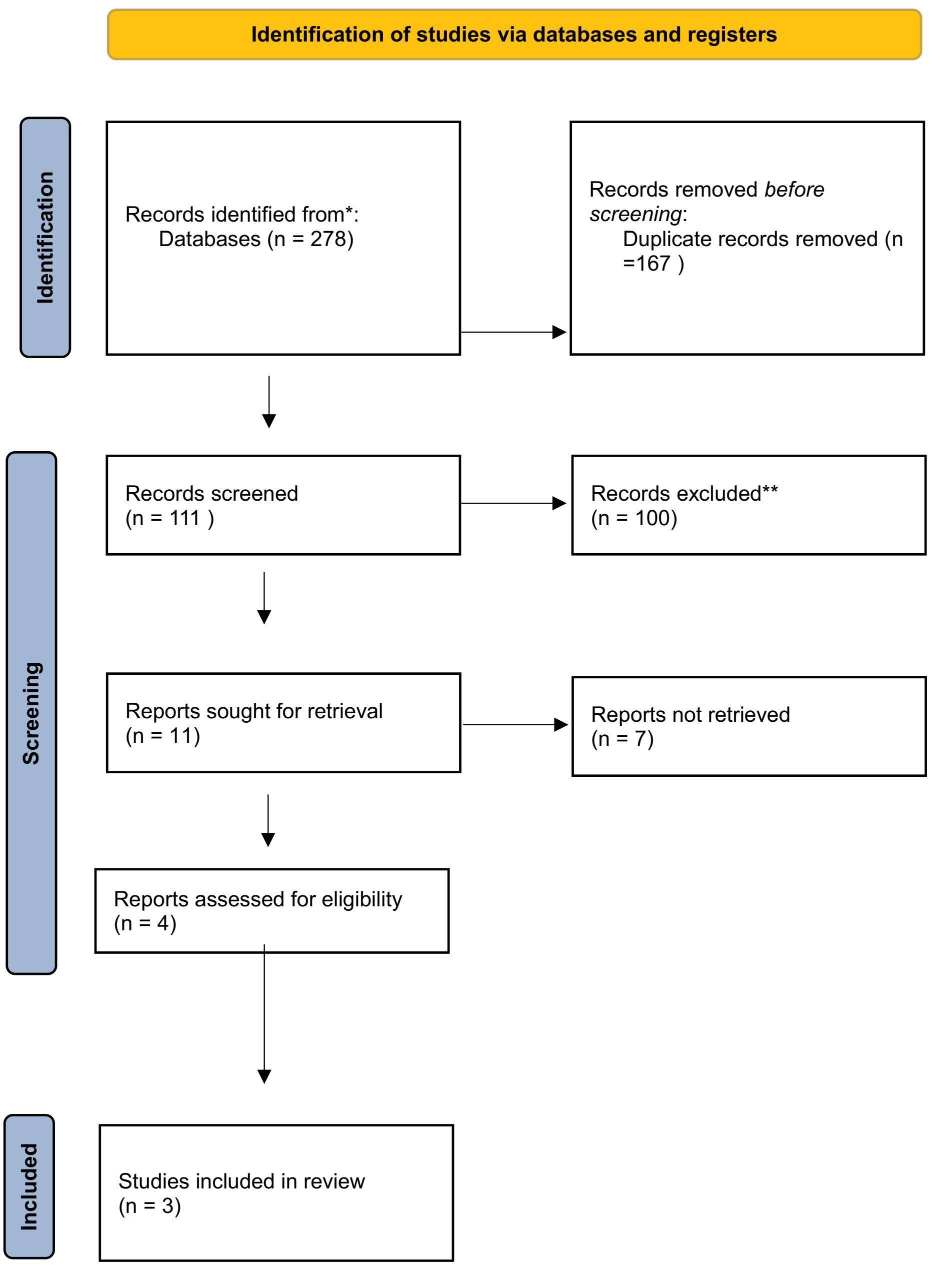

Figure 1. PRISMA flow chart.

changing depending on society's advances and evolving needs. Only articles published in English were used for the research because of the requirement to ease the analysis process. Studies that contained a high risk of bias, incomplete reporting, and lack of proper peer review were excluded from the study to increase the credibility of the results. More importantly, up-to-date research is essential for evidence-based practice, requiring the most viable information[4].

Search strategy

Key search terms used included combinations such as "Artificial Intelligence," "spinal surgery," "AI use in surgery," "reliability," "preparation of predictive models," and "challenges." Boolean operators were applied to refine the search, using terms like "AND," "OR," and "NOT" to limit and expand search results as appropriate. For example, searches using "Artificial Intelligence AND spinal surgery" or "AI AND predictive models" were used to focus specifically on relevant studies.

The inclusion criteria were as follows (Table 1):

- Articles published in the last 5 years (to ensure the research reflects the latest trends in the fast-evolving AI field).
- Peer-reviewed articles in English, to facilitate analysis and ensure quality.
- Studies that specifically examined AI's applications in spine surgery or related fields like predictive modeling.

Exclusion criteria were as follows (Table 1):

- Articles with a high risk of bias or incomplete reporting.
- Non-peer-reviewed sources, such as editorials, commentaries, or opinion pieces.
- Studies focusing on AI applications outside the scope of spine surgery.

The initial search yielded a large number of articles, but after applying the inclusion and exclusion criteria, only three articles were found to meet the criteria and were selected for this review. These articles were summarized and analyzed in Table 2. Future reviews would benefit from more expansive inclusion criteria and a wider range of databases to further strengthen the comprehensiveness of the review.

By using the PRISMA guidelines and a structured search strategy with precise Boolean operators, this review aimed to maintain rigor and ensure a transparent and replicable process for future studies.

Table 1

Inclusion and exclusion criteria for selection of included articles

Criteria type	Criteria description
Inclusion	• *Date of publication*: Articles published within the last 5 years • *Language*: Articles published in English • *Content*: Focus on artificial intelligence in spinal surgery and predictive models
Exclusion	• *Bias and quality*: High risk of bias, incomplete reporting, or lack of peer review • *Outdated information*: Articles older than the set time frame

Discussion

According to De Simone, AI research in surgery mainly focuses on developing semi-autonomous acting devices and robotics capable of executing different interactions with the surgeon but always remaining under his supervision[5]. As a result, there are some areas of AI research in surgery that seem to attract more attention as compared to others. Based on the available literature, the areas of AI research that get the most attention are those with the highest feasibility rate and are likely to be achieved shortly, such as those sectors that enhance the doctor's decision-making process.

Outcome prediction seems to draw the interest of most researchers as they seek to understand the possibility of AI using current information to predict surgery outcomes. Saravi *et al.* focused on the critical advances in deep and machine learning that would have allowed for pattern recognition based on the patient information set that was available to it[6]. Saravi *et al.* employed a hybrid learning machine-learning approach that included unsupervised and supervised techniques, indicating significantly better performance among the hybrid machine-learning models than the traditional ones[6]. The models demonstrated high accuracy, precision, and recall levels, which set them apart from the traditional ones. Saravi *et al.* are just one among the long list of researchers who concluded that AI has the potential to improve spinal surgery significantly[6]. They outperform traditional models through their construction based on both supervised and unsupervised learning techniques. In most instances, they arguably come out stronger with more improved metrics on accuracy, precision, and recall. In one such case, hybrid methods significantly outperformed the traditional methods in surgical outcome predictions. Including such specific performance metrics like higher F1 scores, improved sensitivity, and lower error rates would give a clear idea of exactly where they stand with respect to conventional approaches.

Zhou *et al.* also concluded that AI can significantly increase the accuracy and efficiency of spinal surgery[7]. AI could improve spinal surgery through robotics-assisted surgery, automated surgical planning, image analysis and segmentation, medical decision-making, predictive modeling, and diagnostics[7,8]. Zhou *et al.* employed a systematic literature review and found that the current practice of spinal surgery can significantly benefit from using AI[8]. Similar outcomes can also be found in Joshi *et al.*[9] A systematic review by Joshi *et al.* also identified image analysis and segmentation, predictive modeling and diagnostics, medical decision-making, and automated surgical planning as the primary uses of AI in spinal surgery[9].

Image analysis and segmentation seem to be recurring themes in many studies. Galbusera *et al.* systematically reviewed existing literature focused on machine learning and the use of AI in spine research and surgery[10]. Manual and automated techniques were used to identify the application of AI. However, perhaps the unique aspect of Galbusera *et al.* is its diversion away from just the applications of technology in spinal injury[10]. Galbusera *et al.* discussed the potential challenges of using AI and machine learning in spinal surgery[10]. The main challenge identified was the reliability of AI-based models regarding patient outcomes.

Karnuta *et al.* used clinical datasets from 1000 patients divided into test and training datasets in one of the few studies that developed a predictive model[11]. Support vector machines,

Table 2

Summarizes the three studies included in our review

Study title	Authors	Main focus/objective	Methodology	Key findings	Notable aspects
Artificial intelligence-driven prediction modeling and decision making in spine surgery using hybrid machine learning models	Babak Saravi *et al.*	Application of AI and ML in spine surgery using hybrid models for predictive modeling and decision-making	Review of machine and deep learning advancements for pattern recognition in spine surgery data	Highlights the potential of AI and ML in improving decision-making in spine surgery, with emphasis on integrating multiple data modalities	One of the first comprehensive reviews focusing on AI in spine surgery, discussing patient-specific, AI-driven, multimodal data integration
The application of artificial intelligence in spine surgery	Zhou *et al.*	Comprehensive exploration of AI and ML in spine surgery, focusing on hybrid models	Discussion on the integration of various data types in AI applications for spine surgery, examining the transformation of textual data and multi-input mixed data models	Outlines the potential of AI and ML in enhancing decision-making in spine surgery, with the development of AI-driven, patient-specific tools incorporating multimodal data	Technical focus on AI application in spine surgery, addressing future decision-making with AI-driven, multimodal data integration
Current applications of machine learning for spinal cord tumors	Konstantinos Katsos *et al.*	Use of ML in diagnosing and managing spinal cord tumors, improving diagnostic accuracy, surgical planning, and postoperative outcomes	Review of ML applications in spinal cord tumor diagnosis, surgical planning, and management using classification, regression, and clustering techniques	Highlights ML's potential to revolutionize spinal cord tumor management, aiding in diagnosis, surgical planning, and predicting outcomes	Comprehensive overview of ML applications in spinal cord tumors, identifying benefits and challenges in clinical implementation

AI, artificial intelligence.

random forests, and gradient-boosting algorithms were then employed to construct the predictive model[11] metrics such as F1 score, accuracy, precision, and recall. The research results indicated that the machine learning model had good reliability and responsiveness. However, one major weakness of Karnuta *et al.* was that it was too focused on the payment scheme involving spinal fusion rather than the procedures themselves[11].

There is already a high rate of complications in adult spinal deformity surgery; therefore, scientists are trying to ensure that whatever technology is being introduced can work toward improving outcomes rather than delivering the same rate of errors and complications as human professionals. So far, both Cui *et al.* and Katsos acknowledged how accuracy and reliability remain a challenge regarding the use of AI in spinal surgery[12,13]. According to Cui *et al.*, there is a greater demand for operational efficiency while maintaining imaging and good accuracy and functional report quality in the radiology department[12]. Deep learning (DL) has already demonstrated the capacity to learn appropriate features and classify images with a high accuracy level, once again proving the importance of AI in spinal imaging.

Currently, the three most cited challenges with using AI in spinal surgery include clinical conversion, scattered data, and integration degree. According to Taher *et al.*, the technical infrastructure is limited for data acquisition, access, and storage because not all the data are recorded and permanently stored. In addition, not all the data are digitized and held structurally, which makes interoperability and access a complicated process[14,15].

The effectiveness and performance of AI-based systems in any field, including medical practices such as spine surgery, highly rely on the accuracy and effectiveness of their working data. Several strategies can be put in place that would help to alleviate the problems brought about by bad-quality data. There is a process of data cleaning or preprocessing, which helps to determine and, in turn, eliminate the occurrence of errors or inconsistencies in the data under analysis. In this domain comes the normalization of data, the process of imputing missing values, and the identification of outliers. Another aspect of continued learning is that AI systems can update their models with new data in more accurate and reliable over time. As well, AI systems would be able to cross-reference diverse sources of data and confirm the information to minimize the influence of erroneous or biased data from one source. Further, robust machine learning algorithms—DL in particular—manage big and complex data with an element of complexity such that the latter can capture very intricate patterns and relationships in a way that conventional means could not. Lastly, the AI models must pass through very thorough validation and testing by independent datasets and techniques like cross-validation to make them generalizable and reliable. Together, these measures allow AI to correct and improve its data-based analysis, which ultimately provides more effective and precise results in the surgery of the spine.

Although the potential benefits of AI in spine surgery are documented, it is similarly pertinent to consider and address the important challenges that AI faces. Although AI may offer promise to improve surgical precision, reduce operative times, and improve patient outcomes, a number of barriers to its widespread use exist, including issues related to data quality, ethical considerations, and various difficulties stemming from its integration.

One of the main challenges with AI is related to data quality. AI-based systems rely heavily on valid and full-spectrum data. Inferior data, incomplete data, or datasets replete with bias generate unreliable predictions. For example, there is evidence to show that AI algorithms can only give suboptimal performance when the datasets are either small or not representative, thus skewing predictions and generalization. According to Taher *et al.*, most of the challenges are associated with data acquisition, storage, and digitization, where most health care facilities lack technical infrastructure for appropriate collection and storage of extensive structured data. In addition, medical data are highly scattered; mostly, it is dispersed across different systems, which might not be interoperable, making it more daunting to integrate AI in a clinical setting. Without reliable data, AI models in spine surgery will be degraded to yield less reliable results clinically.

There are also challenges in ethical concerns, such as accountability, patient privacy, and informed consent regarding the use of AI in medical settings. For example, there is a need to ensure accountability, such as determining who is accountable if an AI system makes inappropriate or dangerous recommendations when AI algorithms are being used in clinical decision-making support. The other concern is the bias issue in AI systems. If the information AI uses during training itself is biased by society, for instance, inequities in health care, then those biases will continue to be issued in problems such as disparate treatment outcomes among different population groups. Studies have highlighted that AI models developed from biased datasets disproportionately misdiagnose or undertreat care in minority populations. Ethical issues need to be considered with these problems if AI is ever to be integrated responsibly into health care. Another major barrier to the integration of AI into spine surgery is issues related to integration itself. At the same time, the vast majority of AI models, while very promising in their initial presentations, have been finding it hard to put to work in real clinical life. For example, numerous AI-powered prediction models in health care have reported poor delivery of prospective results from highly controlled research settings to clinical practice involving actual patients.

Karnuta *et al.* further mentioned that though their AI model demonstrated good reliability in a controlled environment, scaling it up for larger and more diverse populations of patients has been difficult. Moreover, integrating this AI with the current clinical workflow requires huge adjustments. For instance, compatibility with the existing electronic health record systems and whether it fits into the clinical decision-making process of surgeons. Overcoming these barriers thus requires collaboration between AI developers, clinicians, and policymakers in ensuring that AI systems can be translated into daily practice with high efficacy and safety. In all, while the promise of AI in spine surgery is great, such application is not devoid of hitches. Issues of data quality, ethical considerations, and barriers to integration have to be critically surmounted to see the full potential of AI in the future. This indeed calls for future research that puts more attention into overcoming these pitfalls with better methods for data collection, a robust structure considering ethics, and the practical integration of AI into clinical practice.

AI has shown marked potential for enhancing the accuracy of a range of spine surgery procedures, including pedicle screw fixation. In implant placement, such an AI-based positioning system could be highly accurate in screw placement; hence, complications related to screw misplacement, among others, are reduced. Apart from the field of pedicle screw fixation, robotic systems have been developed with the guidance of AI, which helps surgeons in achieving spine operations more accurately and efficiently. These enhance surgical precision for advanced imaging in addition to real-time feedback, thus minimizing the operative time. Surgical planning with the help of automation enabled by AI should apply patient-specific data in developing optimum surgical plans, predicting related complications, and enhancing outcomes. Besides, the AI algorithm is good at image processing for the identification of anatomical structures and estimation of pathological conditions with high accuracy, thereby helping in precise navigation during surgery. Predictive modeling using AI would be able to predict the surgical outcome through preoperative data and guide surgeons to make the right decision. As a whole, most AI-based technologies in spine surgery, for instance, robotic-assisted surgery, automated planning, image analysis, and predictive modeling, have shown high accuracy, precision, and recall in the efficiency and safety of carrying out procedures on the spine.

Conclusion

Based on the available literature, specific areas would form the focus of AI use in spinal surgery: image analysis and segmentation, medical decision-making, predictive modeling, and diagnostics. The available literature also confirms that AI is an effective tool that will have a positive contribution as far as spinal surgery is concerned. The technology is still in its infancy stage and will most likely get better with time. However, at the moment, it is important to focus efforts on areas where the technology will be of most use. The integration of AI into spine surgery offers a promising future, with potential benefits ranging from improved surgical accuracy to better patient outcomes. However, realizing this potential requires addressing the challenges head-on, from improving data infrastructure to ensuring the ethical use of AI. As research continues and technology evolves, it is hoped that AI will play an even more transformative role in spine surgery, ushering in a new era of medical advancements.

While AI holds immense potential to revolutionize spine surgery by enhancing accuracy, reducing operative times, and improving efficiency, it is important to acknowledge that this technology is still in its early stages. The full realization of AI's benefits will depend on addressing key challenges, including data quality, ethical concerns, and the need for robust technological infrastructure. As research continues to evolve, AI's role in spine surgery will likely expand, offering even greater improvements in surgical precision and patient outcomes. However, for AI to be safely and effectively integrated into clinical practice, ongoing research and a careful examination of its ethical and practical implications are essential. This future holds promise, but only through thoughtful and rigorous application can AI truly transform spine surgery for the better.

Ethical approval

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Consent

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None.

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