

## Artificial intelligence in spinal surgery

Muhammad Iftikhar Hanif\*; Cathryn Chandrika Chandrasagran; Shi Min Ghui; Soong Mei Ling

**\*Corresponding Author: Muhammad Iftikhar Hanif**

Newcastle University Medicine Malaysia, Malaysia.

Email: Muhammad-Iftikhar.Muhammad-Hanif@newcastle.edu.my

### Abstract

Artificial intelligence is changing the way spinal surgery is done. It is getting better because of developments in machine learning, robotics and image-guided technologies. This review looks at how artificial intelligence is currently being used in spinal surgery. The authors reviewed numerous academic papers from PubMed, Scopus, and Web of Science. It is found that artificial intelligence assists surgeons in diagnosing, planning surgeries, and managing patient's post-operative care. It employs mathematical models to predict patient outcomes. Despite its advantages, artificial intelligence presents its own set of challenges. Data quality is a concern necessitating peer review. Ethical considerations and the high cost of implementation are also significant issues. Artificial intelligence is a valuable tool for surgeons enabling greater precision efficiency and improved patient outcomes. Continued research is essential to ensure compliance with ethical standards and facilitate the integration of artificial intelligence as a safe and standard component of spinal surgery. Its significance for the future of surgery is undeniable.

**Keywords:** Artificial intelligence; Spinal surgery; Machine learning; Robotics; Predictive modelling.

**Abbreviations:** AI: Artificial Intelligence; AR: Augmented Reality; CT: Computed Tomographic; DLR: Deep learning Reconstruction; EMA: European Medicines Agency; FDA: Food and Drug Administration; GDPR: General Data Protection Regulation; HIPAA: Health Insurance Portability and Accountability Act; ML: Machine Learning; MR: Mixed-Reality; MR: Magnetic Resonance; MRI: Magnetic Resonance Imaging; VR: Virtual reality.

### Introduction

Artificial Intelligence (AI) initially became established in clinical practice within image-based fields such as radiology and dermatology, where diagnostic work and pattern recognition inherently met machine learning models. Surgical fields such as neurosurgery and spine surgery present difficult issues for AI integration. They require real-time decision-making, precise anatomical navigation, and require the potential for permanent neurological damage. Despite these difficulties, advances in robotics, intraoperative

imaging, and algorithmic modelling are making spinal surgery one of the most rapidly evolving frontiers for AI application.

Spinal surgery can benefit immensely from the intersection of AI, Machine Learning (ML), robotics, and Mixed-Reality (MR) technologies. These can increase the precision of surgery, reduce operation times during surgery, facilitate real-time predictive decision-making, and reduce patient risk [6]. The intersection of these signals a multidisciplinary shift towards more individualised, data-driven, and technologically advanced approaches to complex surgical care.

The integration of AI algorithms in spinal surgery procedures is essentially collaboration, where clinical specialists, radiologists, engineers, and data experts need to make available pertinent and reproducible tools by contributing to improve radiology exams and patient care [5]. Robotic assistance and mixed reality navigation rely on close hardware-software collaboration, whereas predictive algorithms require high-quality large datasets to access. Hence, the use of AI in spinal surgery is not just dependent on technological advancement but also on overcoming infrastructural, ethical, and regulatory hurdles.

As novel AI platforms and tools continue to emerge at an accelerating rate, scientists and clinicians must judiciously discriminate between experimental models and well-established, clinically applicable solutions [6]. In the absence of a systematic review of the existing literature, the rapid expansion of AI tools in spinal surgery can lead to fragmented evidence and duplicative development, slowing the translation to safe clinical practice [1,7]. The purpose of this review is to synthesise existing literature and provide a clearer comprehension of the clinical readiness, limitations, and direction of AI in spinal surgery.

Spinal surgery, especially in the cervical spine, is technically challenging because of its close proximity to vital neural and vascular structures like the spinal cord, nerve roots, and vertebral arteries. Even slight deviation during surgery may result in disastrous complications [2]. In an effort to avoid these risks, robotic-assisted surgery systems are increasingly being used to improve pedicle screw accuracy, decrease intraoperative risks, and simplify surgical workflow. In the same manner, mixed reality technologies have also emerged as valuable intraoperative adjuncts, enabling surgeons to project virtual anatomical structures directly onto the patient anatomy, thereby increasing spatial awareness and reducing the necessity for traditional external navigation systems [3].

In neurosurgery, ML models are increasingly used to predict outcomes, stratify patients, and make clinical decisions [1]. These models hold high promise with the neurosurgical diagnosis and therapy being intricate in nature. However, their extensive application in daily clinical practice is not yet seen, mainly due to inconsistent reporting, the absence of external validation, and generalisability issues.

Aside from the technical challenges, AI systems also face significant ethical and structural challenges. The majority of clinical data sets contain systemic imbalances which continuously cause minority groups to be underrepresented and continue existing healthcare disparities [4]. Moreover, most of the clinical data are collected for administrative or billing purposes rather than for clinical research, which raises questions on the possibility of using it to create safe AI models.

This systematic review aims to critically evaluate the current and future applications of AI in spine surgery, with a specific focus on ML-based predictive models, robot-assisted spine surgeries, and MR-guided spine navigation systems. It provides a critical analysis of the stage of clinical readiness, inherent limitations, and potential for translation of the above-named technologies during all stages of spine surgical treatment, ranging from diagnostic evaluation to surgical planning, intraoperative guidance, and postoperative management. Besides, it emphasises some of the most relevant ethical, infrastructural, and implementation challenges that may interfere with the safe, equitable, and sustainable translation of AI into daily spinal surgical practice.

More broadly across surgical specialties, AI is improving and has tremendous potential to refine precision, efficiency, and personalised patient treatment. However, spinal surgery has its unique anatomic and procedural complexities that are stressed toward seeking context-sensitive and high-fidelity technological solutions. While such technologies are imminent, including ML-based models and MR-based technologies, much of the literature currently lies in pieces and for stand-alone tools rather than towards an overall framework for clinical application.

The present review critically analyses the multifunctional role of AI across the entire continuum of the perioperative period in spinal surgery. Among the preoperative and diagnostic ones, it designates an application of ML algorithms for imaging analysis, risk stratification, and prediction of surgical outcomes. The intraoperative review addresses robotic platform integration with the aim of robotic pedicle screw placement and real-time intraoperative navigation, and simultaneously investigates the use of MR platforms for the enhancement of anatomy visualisation and navigation. The postoperative review assesses AI-based tools for patient monitoring, complication prediction, and the adaptation of rehabilitation strategies. The review concludes by mentioning the trends that autonomous surgical systems will be developed in the near future and also integration of AI into complementary technologies like virtual reality, big data analytics, and three-dimensional printing will be done.

### **Research questions:**

1. How is AI currently applied in spinal surgery?
2. What are the barriers and limitations on AI in this field?
3. What future advancements in AI are anticipated for spinal surgery?

## **Methodology**

### **Literature search**

Comprehensive literature search was performed in PubMed, Scopus, and Web of Science using a wide variety of search terms and phrases: artificial intelligence, machine learning, deep learning, neurosurgery, spine surgery, spinal robotics, pedicle screws, surgical navigation, augmented reality, virtual reality, mixed reality, computer-assisted surgery, preoperative planning, imaging, accuracy, radiation exposure, predictive modelling.

## **Inclusion criteria**

Peer-reviewed articles  
Focus on AI in spinal surgery  
English language articles  
Published between 2015 and 2025

## **Exclusion criteria**

Non-peer-reviewed sources  
Studies unrelated to spinal surgery or AI  
Non-English publications

## **Data synthesis**

Due to heterogeneity of study designs, AI methodologies, clinical applications, and reported outcome measures, a qualitative narrative synthesis was performed rather than a quantitative meta-analysis.

The included studies were synthesised thematically in accordance with the predefined research questions, with findings grouped into domains encompassing current applications of AI in spinal surgery, associated limitations and barriers to implementations, and anticipated future developments.

## **Quality assessment**

The quality or relevance of the studies was determined by:

- Study design and methodological robustness
- Sample size and clinical relevance
- Outcome reporting clarity and transparency
- Relevance to current practice of spinal surgery

No risk-of-bias assessment tool was used as the key objective of this review is to provide a thematic insight into the current state of evidence, and it is not a point of comparison for intervention effectiveness.

## **Diagnostics and preoperative planning**

AI has begun transforming the diagnosis process and preoperative planning stage of spine surgery. It offers solutions that guide clinicians to make more precise and personalised decisions prior to entering the operating room. Traditionally, diagnosis and surgical planning are, to a significant extent, reliant on the surgeon's expertise in medical image interpretation, spinal alignment evaluation, bone quality evaluation, and determining the most optimal way to perform the surgery. However, these choices can vary across clinicians, and manual reading can be time-consuming for the evaluation of intricate spinal deformities

or subtle pathological changes. AI circumvents this shortcoming by studying medical images and patient data on a scale and depth of detail exceeding usual human pattern recognition. This produces repeatable, objective, and data-driven outcomes [26].

The most important clinical application of AI in spine surgery is medical image analysis. Deep learning platforms, along with machine learning algorithms, have been taught to identify conditions such as lumbar spinal stenosis, vertebral compression fractures, and scoliosis on MRI, CT, or x-ray images directly [26,27-29]. The models learn imaging subtleties that are difficult for the human eye to discern. For instance, AI-powered stenosis grading algorithms can be as reliable for diagnosis as expert radiologists [26], and computerised vertebral fracture detection programs can assist in identifying fragility fractures earlier in the primary care setting [27]. Computerised Cobb angle measurement programs used for the evaluation of scoliosis can assess curvature of the spine with excellent reliability. This reduces inter-observer variability and improves workflow efficiency [28,29].

Apart from that, AI is applied to enhance preoperative planning, particularly for pedicle screw implantation surgeries. The selection of an appropriate screw trajectory, length, and diameter requires accurate knowledge of vertebral anatomy, and mistakes could lead to complications like nerve injury or implant instability. Machine-learning planning algorithms can potentially generate patient-specific vertebrae directly from CT scan and construct suggested screw paths as accurate as the traditional freehand planning methods [31-33]. Research has proven that AI-planning has the capability of possibly improving screw accuracy and removing operative variance [32]. Further, developing advances in deep-learning image reconstruction now allow for the construction of CT-like bone imaging from MRI as a radiation-sparing alternative to preoperative staging [33].

Most importantly, the AI systems are assistive but never independent. The surgeon remains the final authority, integrating individual clinical experience with the guidance of AI. AI as used here is a decision support system that points out anatomic risk zones, improves diagnostic uniformity, and allows subtle, patient-specific operative planning. Through optimising diagnostic interpretation and providing highly personalised preoperative plans, AI makes way for more predictable and safe surgical outcomes even before incision is made.

### **Intraoperative assistance**

Artificial Intelligence (AI) has become increasingly integrated into intraoperative workflows in spinal surgery. Its assistance ranges from surgical navigation to robotic instrumentation to real-time anatomical analysis. All in all, reducing operating time, post-operative complications, and improving patients' quality of life [34].

Firstly, AI-assisted navigation systems have improved pedicle screw placement in thoracolumbar and sacral fracture surgeries. Traditionally, Computed Tomographic (CT)- guided navigation and fluoroscopy-assisted methods have been used, demonstrating improved safety. However, recent developments in AI-supported 3D imaging, combined with robotic navigation, further enhance precision and reduce neurological

and vascular complications [34].

In a study by Schroeder and Staartjes, a hybrid system combining a robotic 3D flat-panel C arm (ArtisZeego), which is capable of performing large volume high-definition 3D scans, along with the Renaissance (Mazor Robotics), which enables the surgeons to calculate the proper trajectory of the screw. This system offers continuous imaging along with real-time motion control. In a retrospective study of 27 patients undergoing percutaneous pedicle screw fixation for traumatic fractures, the study reported a 100% accuracy rate, compared with a 10-15% malposition rate with free-hand techniques. Additionally, a 5% malposition rate was reported using just the robot without continuous fluoroscopy [35].

In addition, studies using similar systems reported an accuracy rate of 96.9%, further strengthening the value of AI navigation systems in spinal surgery [36].

Furthermore, we can reduce the radiation exposure patients receive during these surgeries by using Augmented Reality (AR) and AI. A study by Auloge et al. compared two groups of people who underwent percutaneous vertebroplasty, but the only difference was that one group combined AR and AI, while the other used standard fluoroscopy. It was reported that the AR/AI system reduced patient radiation exposure by 50% [37]. Similarly, in another study by Racadio et al. a 37-49% reduction in radiation exposure was shown by using an AR/AI-guided prototype compared to cone-beam CT-assisted fluoroscopy [38]. However, surgical staff are still prone to exposure, so they have been advised in some studies to leave the room or engage in the use of dedicated shielded operative suits [38].

These findings suggest that AI-enhanced navigation not only improves screw accuracy but also reduces intraoperative radiation exposure.

### **Postoperative care and rehabilitation**

To understand the benefits of AI in spinal surgery, this section introduces how AI learns and then explores its impact on postoperative care and rehabilitation. Simply put, machine learning, a type of artificial intelligence, learns from experience. Rather than programmers writing every rule, computers are given vast amounts of historical data like thousands of anonymised patient records. This data helps them identify complex patterns. It's similar to a seasoned surgeon developing a "gut feeling" through years of experience but here that intuition is quantified, data-driven and scalable to benefit all patients.

In the context of spinal surgery, this is revolutionary. These algorithms can analyse a new patient's unique profile – their age, specific diagnosis, bone density, and co-existing health conditions – and compare it against the known outcomes of thousands of similar past cases. The predictable outcomes include hospital length of stay, postoperative complications, hospital readmission, proximal junctional kyphosis, postoperative pain, quality of life, or mortality after surgery for spinal tumours [14]. The result isn't just a statistic; it's a personalised forecast. It can predict recovery timelines, flag individuals at high risk for readmission, and even suggest which surgical approach might lead to the best long-term outcome for that specific person. Some current available algorithms are already available for use for example Skeletal

Oncology Research Group (SORG) ML algorithm which was developed into an open-access web application for predicting risk of 90-day and 1-year mortality for patients with spinal metastasis post spinal metastasis surgery (SORG Spine Metastases Survival Calculator) [14].

This technology is fundamentally changing patient care from a one-size-fits-all model to a truly personalised journey. By harnessing the hidden stories within our medical data, machine learning gives surgeons a powerful new tool to not just perform surgery, but to expertly guide each individual through their entire recovery, making care smarter, safer, and more human than ever before.

Machine learning has significantly advanced the preoperative prediction of adverse outcomes in Anterior Cervical Discectomy and Fusion (ACDF), directly enhancing postoperative care planning and patient counselling. By leveraging a large national dataset and employing sophisticated algorithms like Random Forest, Karabacak et al. created robust models capable of predicting prolonged length of stay, non-home discharge, readmission, and major complications with high accuracy (AUROCs 0.747-0.846) [8]. The critical integration of explainable AI (XAI) techniques, such as SHapley Additive exPlanations (SHAP), transforms these models from black boxes into transparent tools [8]. This allows surgeons to visually demonstrate to patients their individualised risk profiles based on specific factors like age, comorbidities, and laboratory values. Consequently, this data-driven approach facilitates informed shared decision-making, sets realistic recovery expectations, and enables the implementation of pre-emptive, personalised care pathways to mitigate identified risks, ultimately improving patient preparedness and overall surgical outcomes [8].

Furthermore, the essential role of machine learning extends beyond elective procedures to acute, traumatic spinal trauma, demonstrating its versatility as a future tool for spinal care. In a complementary study, Karabacak and Margetis developed interpretable ML models to predict critical in-hospital outcomes – including mortality and non-home discharge – for patients with traumatic cervical spinal cord injuries (cSCI) [9]. Despite the inherent complexity and urgency of trauma cases, their models achieved strong predictive performance (AUROCs of 0.839 for mortality and 0.815 for non-home discharge), underscoring AI's capability to provide reliable risk stratification even in the most challenging clinical scenarios [9]. The consistent methodology of using these models within an open-access web application emphasises the transition of AI from a research concept to a practical, point-of-care instrument. This body of work, spanning both elective and traumatic spinal surgery, firmly establishes that AI-driven predictive analytics are not merely supplementary but are becoming fundamental to the future of personalised spinal surgery. They empower clinicians to move from population-based statistics to individualised prognostic estimates, thereby revolutionising patient counselling, streamlining resource allocation, and ultimately paving the way for more informed and improved clinical outcomes [8,9].

## Benefits of AI in spinal surgery

The integration of artificial intelligence is revolutionising the procedural aspects of spinal surgery, particularly in surgical planning and image quality. AI-powered software can now rapidly analyse a patient's CT scan to create a detailed 3D model of their spine, allowing for virtual surgical planning. These systems

provide surgeons with data-driven recommendations for pedicle screw trajectories, sizes, and lengths, achieving a high degree of accuracy (Gertzbein grade A in ~80-99% of cases) [10-12] in a fraction of the time it takes even experienced surgeons to plan manually [10-13] such as using less time to bend each rod and rebending manoeuvres when compared to freehand or marker-based methods [14]. Furthermore, in medical imaging, Deep Learning Reconstruction (DLR) algorithms are being used to create Magnetic Resonance (MR) and Computed Tomography (CT) images that are significantly clearer and less noisy than those produced by conventional methods. This advancement means scans can be performed faster, and for CT, with a substantially lower dose of ionising radiation for the patient, without sacrificing image quality [8]. Another advantage of the technology would be that it has the ability to improve the merging of 2-dimensional images (e.g. fluoroscopy) and 3-dimensional images (e.g. volumetric MRI) to create a more vivid and whole picture to allow even better navigation intraoperatively. These AI systems can analyse vast amounts of imaging data rapidly, providing radiologists with precise diagnostic insights and reducing the likelihood of human error [15]. However, this promising technology is not without its drawbacks. A significant concern is that the process of denoising can sometimes be too aggressive, potentially blurring or erasing subtle yet critical pathological details that a radiologist would need to see. There is also the risk that the AI algorithm invents structures or details that are not actually present in the raw data, which could lead to misdiagnosis [8,13]. Therefore, while AI offers tremendous benefits for precision and efficiency, its current role must be that of a powerful assistant to, not a replacement for, the critical eye of the surgeon and radiologist [13].

### **Challenges and limitations**

The validity of AI models for spinal surgery depends heavily on the quality and diversity of data on which they are trained. The majority of the current predictive models are trained using a single institution's data, which makes them less reproducible and less generalisable to broader populations. Systematic reviews of machine learning in neurosurgery have discovered external validation that points to the lack of diversity and independent testing in available datasets [1]. Without external validation across heterogeneous cohorts, such algorithms are prone to causing bias and may fail in practice.

Generalisability is also compromised by variability in imaging protocol, documentation standard, and institutional practice. Segmentation protocol and acquisition parameter variability undermine model strength, and disjunctive storage and lack of standardised formats for storage undermine interoperability across health systems [7]. MR navigation systems, though promising, continue to experience instability, latency, and issues in synchronising virtual and anatomical structures, all undermining precision required for safe spinal intervention [3].

The primary ethical concerns regarding AI integration in spinal surgery are data privacy, informed consent, and responsibility. Large datasets of patients, which are generally required for training models, are of utmost concern regarding confidentiality and secure data sharing is less advanced compared to other fields, and multi-institutional collaboration is challenging [7].

Training data set bias is another important concern. Underrepresentation of certain patient groups increases the risk of disparate performance across groups, thereby exacerbating existing disparities in health outcomes. Opacity of the majority of machine learning models, and deep learning architectures particularly, contributes to these concerns by providing recommendations without explanation, which limits both clinician trust and patient capacity to provide informed consent [4].

Regulatory-wise, the implementation of AI in clinical practice remains sparse. Most published models for spinal surgery are at a proof-of-concept stage, and few have received approval from regulatory bodies. In addition, differences in international legal frameworks, such as HIPAA in the United States and GDPR in Europe, pose additional obstacles to data access and algorithm deployment [7].

Although technically feasible, AI systems are faced with substantial challenges to clinical adoption. Acceptance and training on the part of surgeons are instrumental in adoption but are often limited by AI system opaqueness and the unavailability of proper feedback mechanisms in real time. Although these tools have been promising, their utility in daily life is largely unproven, and there are many applications that exist in the infant stages of development [6].

Financial constraints also restrict adoption. Installation of AI requires heavy investment in infrastructure, equipment updating, and employee training, costs that can be too great for small or underfunded institutions. Even where advanced technologies such as FDA-approved robot platforms exist, pragmatic barriers still exist. For example, current robotic technology for cervical spine surgery continues to have issues with setup, registration, and trajectory planning, which deter their easy incorporation into surgical routines. These technical limitations combined with the added complexity of rigid fixation in cervical surgery, have discouraged broader application [2].

Finally, cost-effectiveness is the issue. Incremental advances in surgical precision might not be justifiable in terms of the enormous up-front costs required to create and maintain AI-augmented systems, particularly without robust evidence linking these technologies with improved long-term patient outcomes. Without clear clinical and economic benefit, widespread application of AI in spinal surgery will be limited.

## **Future Direction of AI in Spinal Surgery**

### **Future of AI**

Although AI in spinal surgery has already made huge progress, there is still plenty more that can be done. Currently, robotic-assisted systems are used to improve pedicle screw placement, reduce intraoperative risks, and postoperative complications. All of this help to improve the flow of the surgical process. In the future, Augmented Reality (AR) and Virtual Reality (VR) can have a notable impact on surgery. Their ability to convert 2D images into 3D models allows surgeons to visualise the patient's anatomy better. It has even been suggested that surgeons can practice on these AR/VR models, which in turn allows them to test different approaches and their respective possibilities. All of these contribute to shorter surgical time and fewer surgical complications, which eventually lead to better overall outcomes for the patient [16].

Additionally, AI and ML also play a vital role postoperatively. With wearable devices, patient progress can be more easily and closely monitored. All of this information can then be delivered to the medical team responsible for the patient's care, providing real-time, up-to-date information on the patient's conditions. It may also enable the team to identify warning signs early, allowing timely intervention, which in turn improves patient outcomes. On top of that, we are collecting a large amount of post-operative data, which can be used to research which surgeries or follow-up care yield the best results for patients [17].

Thirdly, AI can open up a whole new meaning for holistic management by personalising treatment plans according to a patient's anatomy and risk factors. With future development, AI might even be able to consider genetics, lifestyle, and environmental factors to predict and recommend the approach most likely to be successful for each patient [17].

There is endless potential to AI; however, these ideas will only work if they are properly introduced into the healthcare system alongside clear rules and ethical guidelines.

### **Integration of AI into the healthcare system**

Even though AI development is advancing quickly, the bigger question is whether it can be implemented in the healthcare system cost-effectively. Right now, the major problem is cost. The initial setup is costly, making it even more difficult for smaller centres or hospitals to adopt, which leads to differences in access and training [17,18,20]. At the same time, there are no standardised teaching programs for AR/VR surgical tools [16,19].

One way to do this could be to introduce the system step by step. Larger training hospitals can collect data in the first round and refine it before smaller hospitals follow. In addition, we can also advocate for the system to be added to the surgical training programmes [16,19]. By doing so, we are ensuring that future surgeons become familiar with these tools early on. Although initial costs are high, studies show that in the long run, it might save money by reducing surgical time, lowering complication rates and decreasing the number of revision surgeries [18,20,25].

Overall, for AI to be appropriately integrated, hospitals need to commit resources, training programmes need to adapt, and proper evaluation has to be done.

### **Ethical, legal and regulatory frameworks**

As with any new technology, there are ethical considerations to think about. Primarily, data privacy is sensitive information that needs secure acquisition and storage. However, different countries have different approaches. Therefore, international regulations should be applied.

Another consideration is accountability. If something goes wrong based on an AI recommendation, it's unclear whether a surgeon, hospital, or company (the responsible entity) should be held accountable, so standardised expectations should be established.

In addition, there is currently a bias at play. AI training data come from specific patient populations or systems used to train the AI, so it may yield results that are not representative of the general public healthcare population. Since we treat patients from diverse medical backgrounds, it makes sense that transparent data collection and assessment is necessary.

Regulatory bodies such as the FDA and EMA have begun developing frameworks to regulate AI in healthcare. These cover topics such as safety, effectiveness, and data privacy. However, AI technology advances much faster than regulations, making it difficult for regulators to keep up.

## Discussion

### Synthesis of findings and implications for clinical practice

When it comes to spinal surgery, AI is also gradually becoming an important element that increases both efficiency and personalisation of care. On this matter, it is important to note that AI would be useful in image interpretation and decision-making for surgery. Additionally, the use of robots in surgery would increase the efficiency of the procedure by ensuring that the rates of complications are reduced. Finally, for post-surgery care, AI-powered wearables would be useful for monitoring.

This will be further enhanced in the future with AR/VR systems to offer more immersive training and real-time guidance during surgery. AI can also be used for predictive analytics and develop personalised treatment plans, which could change the way we manage our patients. With these changes, we can further personalise spinal surgery to the patient's needs.

However, to incorporate these benefits of AI into clinical practice, a few requirements must be met. Surgeons will have to be provided with structured training in interpreting AI results, along with critical thinking skills and prior clinical experience. Healthcare institutions must invest in the proper infrastructure. Gradual implementation and ongoing evaluation have to be incorporated to ensure safe and fair use of these technologies.

However, these developments face continuous challenges. High costs, unequal access, limited integration into training programs, and unresolved ethical and regulatory issues remain obstacles in diagnostics, surgery, recovery, and future uses. Therefore, cautious application and funding are needed to achieve these goals.

In summary, the clinical effects of AI are significant. It can improve results, efficiency, and personal care. However, these benefits will only come from careful integration and the willingness to invest in these technologies.

### Implications for research

Although using AI in spinal surgery shows great promise, the current evidence remains limited. Most studies focus on small single-centre groups or pilot studies. This limits the extent to which findings can be

generalised to different patient populations and healthcare settings. To address this, future research should emphasise extensive, multicentre validation studies that examine AI applications in real-world settings. Broader datasets will capture demographic and procedural differences [21]. This ensures that algorithms are strong, trustworthy, and can work beyond controlled environments.

Another future research idea could be to explore how well AI complements human skills. Questions about how surgeons and AI can collaborate, the appropriate level of automation, and accountability in decision-making remain open [24]. Studies should look at how AI affects surgeon trust, mental effort, and the flow of work during operations. They should also investigate safe models of shared decision-making between doctors and machines. Additionally, creating and assessing structured training programs for AI and AR/VR technologies will help develop consistent skills across institutions.

Finally, it is also required that work must be carried out to fill the gap of ethics. Issues of data privacy, bias, or equity are still not established in respect to spinal surgery [24]. These issues need to be explored using qualitative research that focuses on both patient and surgeon perspectives, as well as research on law and policy with the ability to keep up with the latest advancements in technology.

In conclusion, the proposals for research that are here emphasised indicate that it is important to do more than innovate on the technology itself. A great amount of evidence is the key for ensuring that the application of AI technology for spinal surgery is both safe and fair.

### **Limitations of the review**

This review has several important limitations to consider. Firstly, the studies on AI in spinal surgery vary significantly in design patient groups and outcome measures. Some focus on imaging-based diagnosis and planning while others examine intraoperative navigation or postoperative monitoring. This variation makes direct comparisons difficult.

Secondly, most published work comes from single-centre or pilot studies with small sample sizes. This restricts the generalisability of the findings. A systematic review of AI in spinal surgery found that most studies were from single institutions, raising concerns about external validity [25]. Thirdly, the fast pace of technological innovation in AI poses a risk of obsolescence. Models and tools discussed in recent literature may soon be outdated as newer systems emerge. For example, a 2024 narrative review claimed that AI in spine surgery has not yet «lived up to the hype», partly because the technology evolves faster than clinical evidence can catch up [21].

Finally, the field faces issues related to publication and funding bias. Many studies are funded by industry, and positive results are more likely to be published. This may skew perceptions of AI's benefits. This concern has been noted in reviews of AI adoption in spinal care [16].

## Conclusion

In conclusion, the future of AI research in spinal surgery is much more complex than the technology itself. Although areas such as robotics, AR/VR, wearables, and personalised planning are very promising, it is likely that the greatest challenge would be integrating such advancements into the medical system, as well as ensuring the regulations are clearly defined from an ethical standpoint. If so, then AI could revolutionise spinal surgery by making it safer, faster, and more effective.

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**Authors Information:** Muhammad Iftikhar Hanif\*; Cathryn Chandrika Chandrasagran; Shi Min Ghui; Soong Mei Ling  
Newcastle University Medicine Malaysia, Malaysia.

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