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Exoscope-assisted spine surgery: Current applications and future directions–A short review

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ABSTRACT

Spine surgery is a critical field that seeks to alleviate pain and restore function in patients with various spinal pathologies. Over the years, spine surgery has seen advancements such as minimally invasive techniques with operative microscopes and robotic surgeries. These techniques, however, demand better visualisation during the procedure. Recently, exoscope-assisted spine surgery has emerged as a promising technological advancement that may revolutionise the field due to its ability to facilitate precise and advanced visualisation techniques that ensure successful outcomes in spine surgeries. The application of exoscopes have improved spine surgeries such as spinal fusion procedures, decompression surgeries, instrumentation surgeries, minimally invasive and complex surgeries. These improvements include enhanced visualisation, improved ergonomics, improved surgical precision, reduced operation times and postoperative infection rates. The integration of robotics in exoscope-assisted spine surgery enables autofocus function, ensuring the integrity of the sterile field, providing superior image quality, resolution and three-dimensional perception. However, challenges such as decrease in depth perception and the lack of long-term follow-up data hinder its widespread adoption. Ethical considerations regarding patient safety, technology dependency, and health inequity add another dimension to these challenges. Despite these challenges, exoscope-assisted spine surgery holds significant potential for transforming clinical practice and improving patient outcomes. This review seeks to provide a concise overview of the benefits and limits of exoscope-assisted spine surgeries, while highlighting its challenges and ethical considerations. Addressing these limitations by conducting large-scale clinical trials and exploring the integration of artificial intelligence (AI) could assist in realising the potential of exoscopes in spine surgery.

1. Introduction

Spine surgery is an important field that addresses various spinal pathologies, aiming to alleviate pain, restore function, and improve patients' overall quality of life (QoL).[1] In recent years, exoscope-assisted spinal surgery has emerged, offering promising advancements by enabling precise and sophisticated visualisation essential for successful surgical outcomes.[2]

Visualisation is critical in spinal surgery, playing an instrumental role in diagnosis, surgical planning, and implementation. Whilst traditional surgical microscopes have long been the mainstay of surgical visualisation, they possess limitations in delivering optimal visual fields.[3] Exoscopes, however, offer superior visualisation, magnification, and adjustable camera angles, surpassing traditional microscopes in these aspects.[4,5] exoscopes confer ergonomic advantages.[6–8] Furthermore, the exoscope may have strong pedagogical advantages.[9,10]

Nonetheless, there are significant challenges to widespread adoption of the exoscope, including decreased depth perception.[10–12] Surgeons have also reported experiencing discomfort due to 3D

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Abbreviations:

TLIF	Transforaminal Lumbar Interbody Fusion
ALIF	Anterior Lumbar Interbody Fusion
ACDF	Anterior Cervical Discectomy and Fusion
QoL:	Quality of Life;
OM	Operative Microscopy
3D	Three-Dimensional
HD	High-Definition
LMICs	Low- and Middle-Income Countries
AI	Artificial Intelligence
MISS	Minimally Invasive Spine Surgery
4K	4K Ultra High Definition
5-ALA	5-aminolevulinic acid
ICG	Indocyanine Green

(three-dimensional) glasses.[9] Further ethical concerns regarding patient safety, dependence on technology, and health inequity compound these challenges. Despite these obstacles, the potential of exoscope-assisted spinal surgery to transform clinical practice is substantial. Consequently, future research must focus on addressing these limitations, integrating robotics and AI, and evaluating long-term patient outcomes robustly.[10]

This review provides an overview of current applications and future directions of exoscope-assisted spinal surgery, with a particular emphasis on its benefits and limitations. This review serves to provide an exhaustive understanding of the latest technology for surgeons, thereby promoting clinical practice, and also provides strategic direction for subsequent research. Recognising the significance of understanding the current state and future prospects of exoscope-assisted spinal surgery is indispensable for surgeons and healthcare professionals, as it will facilitate evidence-based adoption of this technology.

2. Methods

This narrative review focused on the applications and future directions of exoscope technology in spine surgery, adopting a rigorous methodology to ensure an encompassing search of the published literature.

The criteria for inclusion accepted a variety of study designs, such as observational, case–control, cohort, and randomised controlled trials. Studies involving both adult and paediatric populations were considered, and the review considered all manifestations of exoscope-assisted spinal surgery. Only articles written in English were considered. No timeline was applied.

For the literature search, databases such as PubMed, EMBASE, Google Scholar, and the Cochrane Library were used. Search terms included "exoscope-assisted surgery", "spinal surgery", “minimally invasive surgery” and "robotic spine surgery". A manual search was also conducted to identify references from recently published, procedure-specific reviews. Abstracts and unpublished studies were excluded from the review.

The review, employing an exhaustive and methodological approach, aimed to offer a high-quality academic assessment of the present applications and future possibilities of exoscope technology in spine surgery. This process allowed for an extensive synthesis of relevant findings, providing insights potentially applicable to a wide range of surgical procedures.

3. Advantages of exoscope-assisted spine surgery

3.1. Improved visualisation and ergonomics

The past decade has witnessed an incline in preference for exoscope-assisted procedures such as TLIF (transforaminal lumbar interbody fusion), ALIF (anterior lumbar interbody fusion), ACDF (anterior cervical discectomy and fusion), and laminectomy, due to their superior magnification, illumination, and visualisation of the surgical field compared with traditional microscopic techniques.[2,4,6,11,13,14] Additionally, the exoscope provides increased clarity and precision target treatment, which has been associated with a reduction in surgeon fatigue. This reduction is largely due to the ergonomic benefits observed in ALIF, TLIF, and discectomy procedures.[2] The ergonomic benefits, including reduced physical strain and improved manoeuvrability within the surgical field, have been realised in these spinal surgeries, owing to the separation of the surgeon from the optical system.[2,5,6,10,11,13–16] Although currently disputed, some studies in TLIF and ALIF have indicated that the exoscope’s improved depth perception, a key element in spine surgery, may assist surgeons in identifying microstructural anatomy.

These advantages, when combined with the exoscope’s ability to provide unobstructed access to small and deep surgical fields, create ample room for the insertion and manipulation of instruments.[4]

3.2. Improved surgical outcomes and efficiency

The exoscope’s superior magnification and high-definition (HD), 3D view have been associated with a lower incidence of postoperative complications such as dural tears and neural injuries in spine surgeries including TLIF, ALIF, ACDF, and laminectomy.[2,5,6,8,9,13,15,17] Notably, cervical discectomies conducted using 3D exoscopes have reported fewer complications, including vascular and nerve injuries, rupture of internal fixation, and displacement of interbody fusion cages, alongside a reduction in surgical time.[11,14,18] Such improvements may mitigate the viewing limitations commonly encountered in conventional endoscopic procedures.[6] Specifically, in ALIF procedures, postoperative courses have been uneventful with minimal pain, enabling early patient mobilisation and shorter hospital stays.[4]

The application of exoscopes in TLIF and ALIF procedures has been correlated with improved patient outcomes, as evidenced by reduced back pain and disability scores, and a lack of general and instrument-related complications.[4,9] Moreover, the exoscope’s depth of field, the extent of which is currently under debate when compared to the traditional operating microscope, has been credited for reducing the frequency and duration of repositioning and refocusing during surgical procedures.[9]

Although currently disputed, the increased depth of field, in conjunction with ergonomics, ease of movement and the assistant engagement, could all contribute to a reduction in surgical time, which is known to decrease patient perioperative complications.[6,14,19] This could potentially improve efficiency and clinical outcomes while reducing operation time and complication rates.[2,9]

The incorporation of robotics in exoscope-assisted spine surgery enables surgeons to achieve challenging visualisation angles. Enabled by a robotic arm with autofocus capabilities, this integration results in superior image quality, resolution, and 3D perception.[5,13,17] Moreover, by minimising the level and frequency of physical contact required with the microscope, the integration of robotics with the exoscope further ensures the integrity of the sterile field.[5]

The exoscope’s comparatively diminutive size allows for ease of use from the early surgical stages, such as cervical soft tissue dissection, neural structure decompression, and cage insertion, all of which require unrestricted manoeuvrability of the screw and cage holders under direct vision.[20] The 3D robotic digital microscope integrated in exoscope-assisted spine surgery has demonstrated satisfactory outcomes in various procedures, incorporating an endoscopic arm to facilitate the execution of minimally invasive approaches.[13,17]

Unlike the operating microscope (OM), whose larger size can sometimes prove cumbersome, the exoscope's comparatively diminutive size offers advantages from the early stages of surgery. This is particularly beneficial during procedures such as cervical soft tissue dissection, neural structure decompression, and cage insertion, where unrestricted manoeuvrability of the screw and cage holders under direct vision is critical.[20] The 3D robotic digital microscope integrated into exoscope-assisted spine surgery has shown promising outcomes in various procedures. The integration of this technology employs an endoscopic arm, which assists in carrying out minimally invasive approaches.[13,17]

3.3. Teamwork and educational advantages

The integration of exoscopes into surgical practice has not only improved procedure quality but also proven to be a valuable tool for education and teamwork.[2,3,9] Unlike traditional operative microscopy (OM) that provides a limited view, the exoscope offers shared 3D HD visualisation. This inclusive perspective allows surgeons, anaesthetists, nurses, and medical students to cooperatively participate in procedures, enriching their learning experience.[9]

Adapting to the exoscope comes with a shorter learning curve compared to endoscopic techniques.[2,4,8,12] The exoscope's user-friendly nature, coupled with the inclusive view from the 4K (4K Ultra High Definition) monitor, make it an attractive technological upgrade.[6,14]

A noteworthy capability of the exoscope is its ability to create high-quality videos from the surgeon's viewpoint. These offer superior didactic potential for surgical anatomy instruction compared to videos recorded through microscopes.[20] The use of robotic exoscope systems has improved communication and collaboration among multidisciplinary teams, largely due to the shared viewing platform.[13,17] This inclusivity makes these systems an especially valuable tool in teaching environments where training residents is a priority, marking a new era of accuracy, safety, and innovation in spine surgery.[10] (see Table 1)

A summary of the advantages of applying exoscopes in spine surgery is provided in Table 2.

Table 1
Summary of methodology.

Methodology Steps	Description
Literature Search	PubMed, EMBASE, Google Scholar, and the Cochrane Library.
Inclusion Criteria	- Randomised controlled trials, prospective and retrospective cohort studies, case–control studies, case series. - Studies involving both paediatric and adult populations. - Studies involving comorbidity and previous treatments. - No timeline restrictions
Exclusion Criteria	- Standalone abstracts - Case reports - Posters - Unpublished or non-peer-reviewed studies - Non-English studies
Search Terms	Keywords include "exoscope-assisted surgery", "spinal surgery", "minimally invasive surgery", "robotic surgery"
Additional Search	A manual search was performed to include references from recently published procedure-specific and disease-specific reviews related to exoscope-assisted spinal surgery.
Sample Size Requirement	No strict sample size requirement

Table 2
Advantages of exoscope in spine surgeries.

Advantages	Description
Improved Visualisation and Ergonomics[2,4–6,10,11,13–16]	• Superior magnification, illumination and visualisation compared to traditional OM. • Excellent clarity and precision target treatment, reducing surgeon fatigue. • Ergonomic benefits, mitigating physical pain. • Enhanced surgical field manoeuvrability, as the surgeon is separated from the optical system. • Unobstructed access and deep surgical fields. • Improved depth perception. • Superior image quality, resolution, and 3D perception, made possible by a robotic arm with autofocus.
Improved Surgical Outcomes and Efficiency[2,5,6,8,9,13,15,17]	• Low incidence of postoperative complications such as dural tears and neural injuries. • No postoperative complication, enabling early patient mobilisation and shorter hospital stays. • Decreased back pain and disability scores. • Reduction in perioperative bleeding. • Ensures the integrity of the sterile field. • Ease of use for early surgical stages, such as cervical soft tissue dissection and cage insertion.
Teamwork and Educational Advantages[2–4,6,8–10,12–14,17]	• Real-time observation by the entire surgical team, due to the 3D HD monitor. • Facilitates cooperation between surgeons, anaesthesiologists, nurses and medical students. • Improved teamwork, enhanced collaboration. • Shorter learning curve, user-friendly. • Immersive surgical experience. • Creation of high-quality video.

4. Limitations, ethical considerations and future prospects in exoscope-assisted spine surgery

4.1. Current limitations of exoscope-assisted spine surgery

Despite several benefits, such superior visualisation and improved ergonomics, the adoption of exoscope in spine surgery isn't without its challenges.[2]

While the benefits of exoscope-assisted spine surgery are increasingly recognised, there is ongoing debate about the effect of exoscope-assisted surgery on depth perception, in comparison to traditional OM. Various studies, spanning procedures like ACDF, TLIF, long approaches, and robotic surgery, have suggested that exoscope-assisted spine surgery may provide inferior depth perception, a quality inherently stronger in conventional OM.[7,8,10–13] This limitation has presented a considerable obstacle, causing hesitation to adopt exoscopic techniques, despite attempts to rectify the issue with flat view adaptation.[10,13]

Moreover, a study found the image quality of current 3D 4K monitors to be inferior to optical visualisation in simulated spine surgery.[21] In terms of perioperative bleeding, while one study found a reduction in two-level TLIF procedures using 3D exoscope,[7] another reported higher average blood loss compared to the OM group in ACDF procedures.[8]

In addition, the combination of robotic integration and exoscope spine surgery has been observed to compromise image sharpness at high magnification, especially compared to traditional microscopy. The Modus V system, for instance, slows down procedures and increases risk due to its need for 3D imaging.[13] Moreover, the absence of fluorescence modules like 5-ALA (5-aminolevulinic acid) and ICG (Indocyanine

Green) also presents a disadvantage.[13]

Operational changes required for exoscope use and potential discomfort due to 3D glasses are additional concerns.[2,9] Also, the significant cost of integrated systems, like the Modus V Synaptive System priced at GBP £521,000 to £580,000,[5] may slow adoption, especially in low and middle-income countries.[8]

A notable gap exists in literature regarding long-term data on the benefits and potential complications of exoscope-assisted spine surgery. This emphasises the need for future research for a comprehensive understanding of its implications on patient outcomes. Therefore, while exoscope and robotic integration shows promise, addressing these limitations is critical for its broad adoption and optimal use. The limitations and ethical challenges with using exoscope-assisted spine surgery have been illustrated in Fig. 1.

4.2. Ethical considerations in exoscope-assisted spine surgery

Exoscope-assisted spine surgeries introduce multiple ethical issues that healthcare professionals must carefully address to ensure patient safety, autonomy, and responsible technology use.

Firstly, the novel nature of exoscopes emphasises the need for thorough informed consent. Patients should receive detailed information about the procedure and the alternative of traditional OM. The proposal to use an exoscope must be discussed preoperatively, with assurance that patients have the capacity to make informed decisions and provide consent.[22] Moreover, despite the scarcity of literature on exoscope-assisted spine surgery and the pressing need for research to fully assess its effectiveness, maintaining the security of patient data is of critical importance, requiring strict adherence to ethical guidelines.

Technology dependence is another ethical concern. Although exoscopes can improve visualisation and precision,[2,13] surgeons must avoid over-reliance on this technology. The surgeon's clinical judgement and

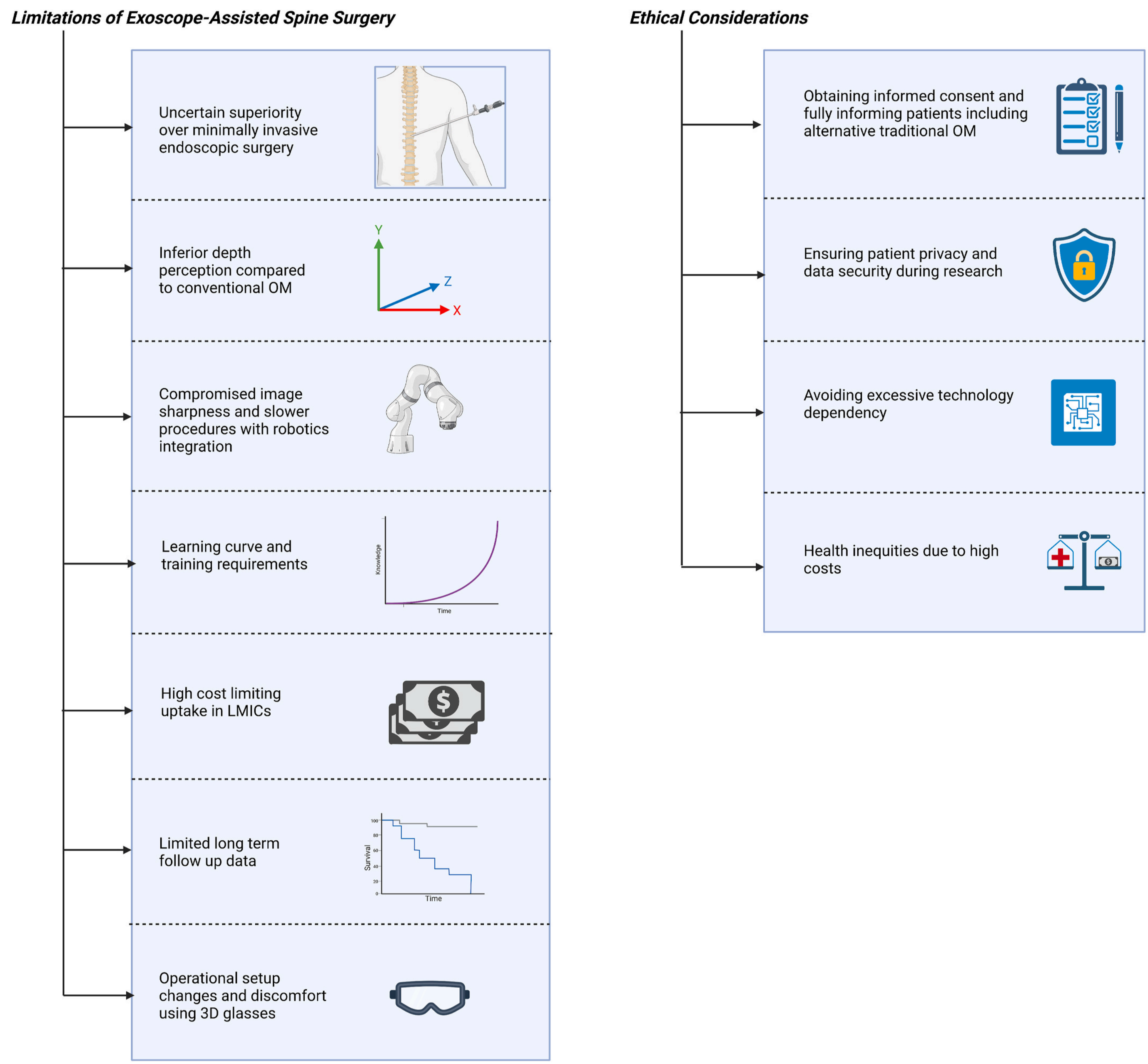

Fig. 1. Limitations and Ethical Challenges with Using exoscope-Assisted Spine Surgery.

expertise should remain central to decision-making in spine surgery.

The introduction of exoscopes might also widen health inequities globally. The high cost of the exoscope technology, between GBP £521,000 and £580,000,[5] could slow its adoption in low-resource settings, particularly in LMICs, thereby exacerbating healthcare disparities worldwide. Thus, it's essential to develop strategies for cost-effective exoscope use.[23]

By considering and addressing these ethical considerations, healthcare professionals can responsibly integrate exoscope technology into spine surgery while prioritising patient welfare.

4.3. *Future prospects for exoscope integration in spine surgery*

The use of exoscopes in spine surgery has demonstrated multiple advantages for both spine surgeons and patients, with improved visualisation and ergonomics for surgeons, and reduced complications and significantly improved symptoms for patients.[6,13,14] Given the discordant conclusions drawn by several studies, large-scale clinical trials, preferably randomised, and comparative studies are vital to establish the impact of exoscope use.[10,23] Multicenter trials focusing on complex procedures could provide a more nuanced understanding, potentially influencing the future application of this technology in spine surgery. Addressing ethical limitations should also occur to encourage more widespread adoption of exoscope-assisted surgery.

Regarding robotic integration, a significant area for improvement in the Modus V system is the addition of a 3D camera.[13] Furthermore, introducing fluorescence modules such 5-ALA and ICG, and ensuring endoscopic and navigation compatibility could broaden the spectrum of procedures. Developing tissue recognition features such as digital and confocal microscopes for pathology might also prove valuable for performing safer surgery.[13]

Considering the novelty of exoscopes, comprehensive training in the laboratory may be beneficial before clinical application.[13] This approach ensures that neurosurgeons are comfortable using the new technology and can maintain patient safety. Challenges require innovative solutions to overcome operational setup changes and tackle the potential ethical concern of increasing health inequity. For instance, a new, affordable exoscope-assisted MISS setup, which is easy to prepare and suitable for use in low-and-middle-income countries (LMICs).[3,23] Preliminary evidence has demonstrated that this cost-effective exoscope is safe and feasible for TLIF, and can be obtained for a fraction of the cost of conventional microscopes.[3] The advantages of this system necessitate further studies to evaluate its safety and efficacy.

Finally, the implementation of AI models in exoscope-assisted spinal surgery could be a promising avenue to explore. The integration of AI subsets, such as augmented reality, has been shown to reduce shifts in spine surgeons' focus and procedure disruption.[24] This application could be adapted to exoscope-assisted spine surgery.

The future prospects of exoscope-assisted spine surgery and its integration with robotics and potentially augmented reality are likely to catalyse further advancements in this field. As the technology matures and gains more widespread acceptance, it has the potential to improve surgical outcomes and minimise complications. Future prospects with exoscope-assisted spine surgery have been illustrated in Fig. 2.

5. Study limitations

While this review seeks to evaluate exoscope technology in spine surgery comprehensively, it is important to acknowledge certain limitations. The scope, while extensive, may only address a selection of the emerging applications and developments of exoscopes in this field. There may exist a publication bias as positive or significant findings are

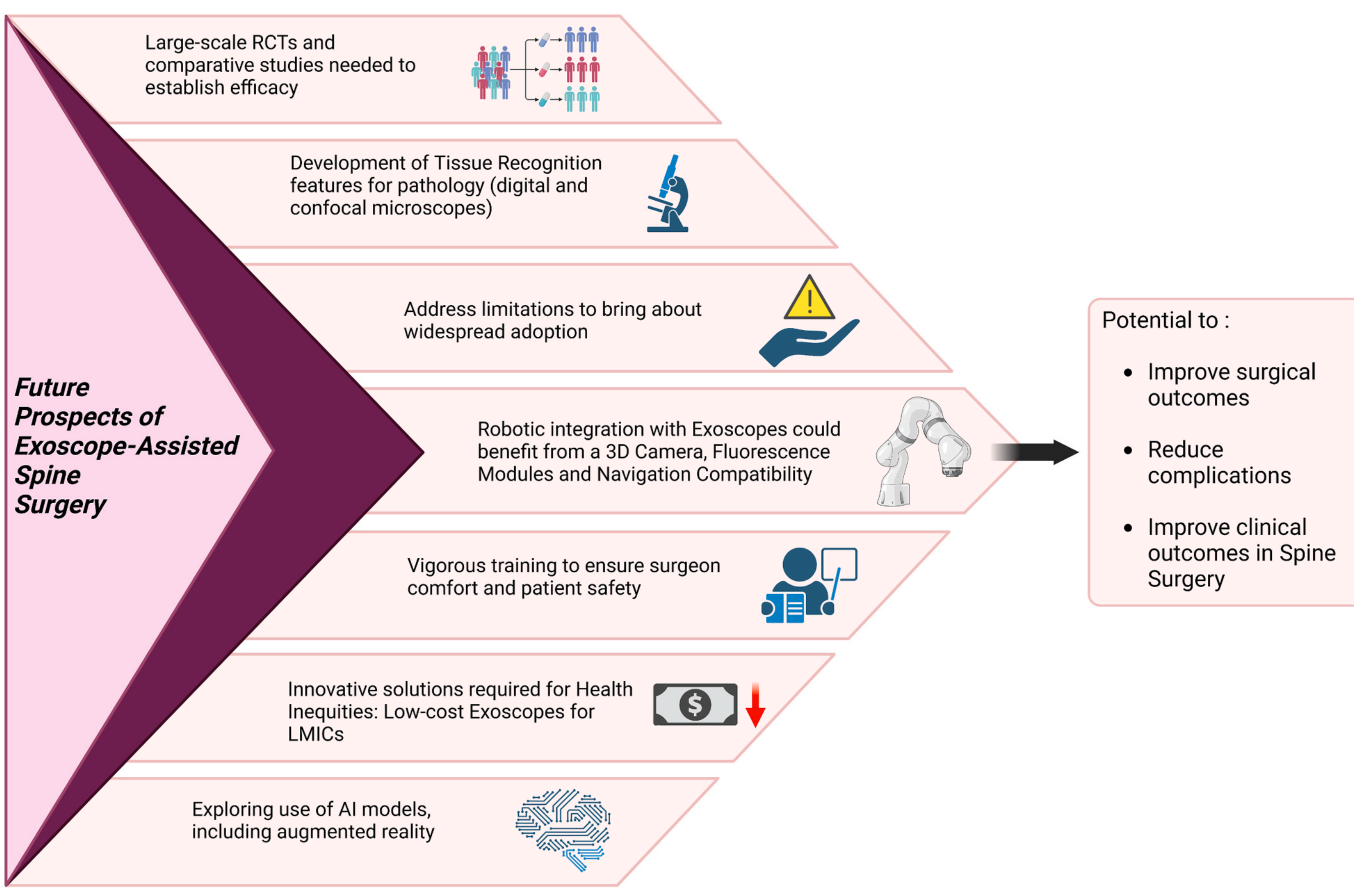

Fig. 2. Future Prospects with exoscope-Assisted Spine Surgery.

more often published, which could potentially sway overall conclusions. The quality and heterogeneity of the included studies could introduce variability into the data and results.

There is a lack of long-term follow-up data in the literature, restricting a thorough evaluation of persistent benefits and possible complications. The specified inclusion criteria might introduce bias, and some pertinent studies may have been unintentionally omitted. A detailed cost-effectiveness analysis was not undertaken, and further investigation into the learning curve associated with transitioning to exoscope-assisted methods is required.

Considering the novelty of the exoscope as a technology, the available literature on the topic is limited and, in certain instances, conflicting. There is a scarcity of large-scale clinical trials, and some studies present conflicting conclusions. For instance, some studies reporting superior depth perception and a greater depth of field[2,9,14] and others indicating poorer depth perception with the exoscope compared to the OM.[7,8,10–13] Additionally, several studies do not differentiate the outcomes of various surgical procedures.[2,14,15] Consequently, the conclusions drawn may lack comprehensiveness and definitiveness.

Lastly, this review could be subject to language bias. Only full-text English articles were eligible for inclusion, meaning that pertinent studies may have been overlooked. To overcome this limitation, future reviews should engage language experts to ensure the inclusion of all relevant non-English articles on the subject.

6. Conclusion

In conclusion, exoscope technology holds considerable promise for improving spine surgery, providing superior visualisation, ergonomics, and surgical precision. The integration of robotics further augments its potential for facilitating safer and more efficient procedures. Although certain limitations and ethical considerations currently exist, it is likely that ongoing advancements and training will overcome these challenges, paving the way for more widespread adoption. As additional clinical evidence emerges, exoscope-assisted spine surgery has the potential to significantly transform surgical outcomes and patient experiences, marking a notable advancement in the field of spine surgery.

Transparency declaration

TF, the lead author (the manuscript's guarantor), affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study have been explained.

Ethics approval and consent to participate

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Data availability

No additional data available.

CRediT authorship contribution statement

Tomas Ferreira: Writing – original draft, Writing – review & editing, Data curation, Validation, Supervision, Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization. **Sakshi Roy:** Writing – review & editing, Investigation, Methodology, Validation, Writing – original draft, Data curation, Formal analysis, Visualization. **Joecelyn Kirani Tan:** Methodology, Writing – original draft, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – review & editing. **Wireko Andrew Awuah:** Investigation, Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Vallabh Shet:** Visualization, Methodology, Writing – original draft, Data curation, Formal analysis, Investigation, Validation, Writing – review & editing. **Favour Tope Adebusoye:** Data curation, Writing – review & editing, Validation, Formal analysis, Visualization, Investigation, Methodology, Writing – original draft. **Adrenito Nicolas:** Writing – review & editing, Writing – original draft, Data curation, Validation, Investigation, Visualization, Conceptualization, Methodology. **Toufik Abdul-Rahman:** Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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