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Research Article

From Microscope to Exoscope: Evolution of Visualization Technology in Neurosurgical Practice, a Narrative Review

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ABSTRACT

Background: The operating microscope (OM) has been a foundational tool in neurosurgery since the 1960s, providing essential visualization for complex surgeries. Nevertheless, ergonomics, depth of field, and collaboration between team techniques have become limiting factors leading to the development of the exoscope. The exoscope is fitted with high-definition (HD) and three-dimensional (3D) imaging, which are expected to enhance comfort among the surgeons and surgeon's outcomes.
Methods: A literature review was conducted using PubMed and Embase. A total of 24 studies published from 2021 to 2025 were included, which covered exoscopes in cranial, spinal, and peripheral nerve operations. They gathered information on the model of exoscopes, visualization (2D, 3D, 4K), and surgical outcomes (complications and conversion to OM).
Results: Exoscopes lead to high ergonomics of surgeons through the easing of neck pains and workflow advantages. The research is unanimous in terms of increased 3D visualization, deep perception, and surgeon fatigue. Nevertheless, there are still the problems of high start-up costs, high learning cost, and occasional technical restriction, especially when surgeries are in deep seats. The success rate of conversion of exoscopes into active microscopes as a result of these problems is quite low (5-15%). Exoscopes have the advantage of being ergonomic and educative, although they are more expensive and the learning curve prevents their use. Long-term outcomes and cost-effectiveness should be further studied in order to fully determine their effects on neurosurgical practice.
Conclusion: Exoscopes have incumbent potentials positive to conventional OM especially with regard to ergonomics and surgical accuracy. The difficulty of cost and learning curves will however be overcome to make their widespread adoption.

Keywords: Exoscope, Neurosurgery, Visualization, Ergonomics, Surgical Precision.

INTRODUCTION

Neurosurgical practice has a very strong pillar in medical visualization that enables the process of carrying out complex surgeries to possess the tools the surgeons require. The operating microscope (OM) has become the gold standard in magnification, illumination, and stereoscopic vision that has to be used to provide successful cranial and spinal surgical interventions because it was first presented in the 1960s (Kriss and Kriss, 1998). This device allowed neurosurgeons to be more accurate and visible in carrying out their surgeries and this mostly increased the success in brain tumors, aneurysms, and spinal surgery procedures (Mamelak et al., 2008; Langer et al., 2017). However, the OM has many disadvantages, including the aspects of ergonomics and depth of field or the likelihood to share the view of the surgical space with the entire operating team (Muhammad et al., 2019; Siller et al., 2020).

During the past couple of years, digital imaging tools have resulted in the development of the exoscope, the high-definition (HD), and the three-dimensional (3D) system of visualization that are slowly encroaching on the market power of the operating microscope (Montemurro et al., 2022). Some advantages of the exoscope compared to the traditional microscopes are the ergonomic superior design, extended field of view, and the availability of the surgeon to observe the field of operation in real time, accompanied by the entire surgical team (Sack et al., 2018). Moreover, the exoscope has increased depth perception and it can be more easily combined with digital technology, e.g. neuronavigation systems, which are becoming a more popular in neurosurgery (Piquer et al., 2014; Siller et al., 2020).

The development of neurosurgical visualization technologies has been in tune with the greater technological innovation in the medical sphere where this area is constantly being altered by new tools and methods. Since the popularization of the exoscope, the gadget has proven to improve the results of surgery and patient safety, i.e., reducing the fatigue of a surgeon and improving the efficiency of the working process (Ricciardi et al., 2019). These systems have been specifically useful in training and educating with providing shared and 3D visualization that can provide value to the learning of medical students, residents, and surgical employees (Ahmad et al., 2020). However, with all these positive aspects, there are difficulties that are involved in the transition of the microscope to exoscope. Surgeons need learning curve, the preliminary expenses are high, and even deep-seated or complex surgical corridors can be a problem (Burkhardt et al., 2020; Teo et al., 2020).

This narrative review discusses the effects of exoscopes on neurosurgery, contrasts their functionality with the traditional operating microscopes on the basis of visualization quality, ergonomics, surgical outcomes, and learning value. This paper will identify the potential of the exoscope to transform neurosurgical practice and, by analyzing the existing literature on the topic, mentions the position of the exoscope in reshaping the future of the field.

MATERIAL & METHODS

Literature Search

A comprehensive literature search was performed on PubMed and Embase databases to locate research that assessed the application of exoscopes in neurosurgery. The search was carried out in accordance with PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which guarantees the use of a rigorous review process. The search terms were: exoscope, exoscopic visualization, neurosurgery, brain, and spine, and surgical visualization. Both restore operator (AND) and operator (OR) were used to maximize the sensitivity and specificity of the search by combining the following keywords. Table 1 presents the detailed search strategy in each database.

The inclusion criteria included the following: original research work (case series, cohort studies, or clinical trials), which explained the application of exoscopes in neurosurgery (both brain and spine surgery), and lab experiments. Research articles describing the application of exoscopes with 2D and 3D imaging systems, and 3D 4K imaging, among others, were included. The exclusion criteria were: (1) non-English publications, (2) review articles, (3) inadequate data in the study, and (4) studies that were not associated with neurosurgery or exoscopic visualization.

Table 1: Search Syntax and Strategy

Database	Search Syntax	Keywords	Accessed On
PubMed	("exoscope" OR "exoscopic visualization") AND ("neurosurgery" OR "brain" OR "spine" OR "surgical visualization")	exoscope, exoscopic visualization, neurosurgery, brain, spine, surgical visualization	10 October 2025
Embase	("exoscope" OR "exoscopic visualization") AND ("neurosurgery" OR "brain" OR "spine" OR "3D imaging")	exoscope, exoscopic visualization, neurosurgery, 3D imaging, brain, spine	10 October 2025

Data Collection

Based on the chosen articles, the data were extracted regarding the following critical parameters: 1) The number of neurosurgical procedures undertaken with the exoscope, by type (brain tumors, vascular procedures, spinal surgery, and peripheral nerve procedures) and applications based on a laboratory; 2) Details of the manufacturer and model of the exoscope (Coast of 2D or 3D visualization was used); 3) Specifics on the visualization settings (e.g., 2D, 3D, or 4K visualization). Assessed surgical complications that included the incidence of cases when changing the exoscope to the operating microscope (OM) during surgery; 4) The pros and cons cited by the authors, including image quality, field of view, ergonomics, surgical team interaction, learning utility, depth perception and operative time.

Outcomes

The main aim of the review was to recognize the most typical operations conducted under the exoscope, its effects on surgical operations, occurrence of complications and how often surgeries can be switched to the OM. The secondary aim was to examine the advantages and disadvantages of the exoscope that were reported most frequently by the authors in the literature. This involved its performance in regard to video image quality, the clarity of the surgical field, ease of handling, ergonomic advantages, educational worth, and efficiency broadly regarding the duration of the operative and workflow. These were evaluated in order to provide an overview of the strengths and weaknesses of the exoscope technology in the neurosurgical practice.

RESULTS

A total of 50 articles were identified through the database search. A total of 50 eligible records were screened after elimination of duplicates. After this 24 articles were considered eligible to get full-text examination and satisfy the predefined inclusion criteria to this research study. These articles were incorporated into the final synthesis.

In these studies, the exoscope greatly increased the depth perception and ergonomics of the patient, especially during intricate surgeries like brain tumors operations and spinal surgeries. Surgeon fatigue was also minimized by the application of the exoscope which is associated with efficiency and accuracy in surgeries. According to these findings, there is an increase in the use of exoscope in neurosurgery that provides a definite benefit in both the quality of the surgical results and the comfort of the surgical team.

The exclusion criterion was: (1) articles in other languages than English (3 articles), (2) review articles (5 articles), and (3) articles with incomplete or dearthy data (18 articles).

Surgical Applications and Procedures Types

Many neurosurgical procedures have been carried out using exoscope, including those of the brain, spine and on the peripheral nerves. In four studies, the exoscope was implemented in 15 to 30 surgeries each. The procedures of which consisted included brain tumor resections, vascular surgeries, spine surgeries, and selective dorsal rhizotomy. The visualization of the exoscope was 2D to 3D, and 4K, based on the study. Interestingly, the use of exoscopes saw improvement of depth perception and ergonomic functions, less surgeon fatigue especially in brain tumor and vascular surgeries. These findings highlight the significance of exoscope use in enhancing the accuracy and comfort in the course of performing complex neurosurgical surgeries.

Table 2: Surgical Applications and Procedures Using Exoscope

Study	Procedure Type	Number of Surgeries	Visualization Type	Exoscope Model	Main Findings
Abramovic et al. (2022)	Brain Tumor, Vascular Surgery	20	3D Visualization	Digital Exoscope	Enhanced depth perception and ergonomic improvements
Barbotti et al. (2024)	Selective Dorsal Rhizotomy	15	2D Visualization	Custom Exoscope	Successful in pediatric neurosurgery with high precision
Bin-Alamer et al. (2023)	Brain Tumor Resection	30	3D and 4K	Robotic Exoscope	Improved tumor visualization with reduced surgeon fatigue
Iqbal et al. (2024)	Spine Surgery	25	3D Visualization	Digital Exoscope	Faster operative time and less strain on surgeons

Comparison between Exoscope and Operating Microscope

In a comparison between the exoscope and the old operating microscope (OM), the exoscope has a number of strengths especially in terms of ergonomics and opticalization. Research in several operations indicated that exoscope has a bigger field of view and higher 3D imaging; this feature contributes to decreasing the strain in the neck and enhancing comfort in general terms among the surgeon. The disadvantageous factors were however attributed to the high initial expense and maintenance of the exoscope and increased learning curve. Comparatively, although the OM used offered better depth perception and was optimal in deep-seated lesions, it was linked with increased discomfort on the side of the surgeon and reduced field view on the team. Such results emphasize the trade-offs between the advantages of the exoscope and the established benefits that were achieved with the use of the traditional OM.

Table 3: Comparison of Exoscope and Operating Microscope (OM)

Study	**Procedure Type**	**Exoscope vs OM**	**Advantages of Exoscope**	**Disadvantages of Exoscope**
Steinhilber et al. (2023)	Microsurgery	Exoscope	Better ergonomics and larger field of view	Longer learning curve
Haeren et al. (2022)	Aneurysm Surgery	OM	Enhanced depth perception and stereoscopic vision	Decreased surgeon comfort and field view
Schupper et al. (2023)	Neurosurgery	Exoscope	Ergonomically superior with 3D visualization	Higher initial cost
Raheja et al. (2021)	General Neurosurgery	OM	Better for deep-seated lesions	Reduced image clarity

Ergonomic and Workflow Impact of Exoscopes

Ergonomic advantages of the exoscope are plain to see with research on various neurosurgical operations demonstrating a decrease in neck strain and fatigue on the part of the surgeon. Surgeons reported that their operations became more comfortable, particularly in a long-distance operation due to the flexibility of exoscope construction, and positioning of exoscope more conveniently compared to the old operating microscope. Also, the possibility of the whole surgical team to have the same viewing of the surgical field in real-time may be considered as one of the most important benefits of the exoscope usage. The intended collaborative can not only improve teamwork and decision-making, including overall the surgical process, which may cause shorter operating hours and better coordination.

Table 4: Ergonomic and Workflow Impact of Exoscopes

Study	**Procedure Type**	**Ergonomic Impact**	**Surgical Team Interaction**	**Workflow Efficiency**
Abramovic et al. (2022)	Brain Surgery	Reduced surgeon neck strain	Real-time shared visualization	Improved coordination and teamwork
Fiani et al. (2021)	Spine Surgery	Increased comfort and less fatigue	Surgeons, residents, and staff can view together	More streamlined surgical procedures
Steinhilber et al. (2023)	Microneurosurgery	Superior postural ergonomics	Collaborative viewing with entire team	Increased workflow efficiency due to shared visualization
Lingl et al. (2025)	Head & Neck Surgery	No significant strain on surgeon	Enhanced collaboration and training opportunities	Improved decision-making speed

Surgical Outcomes and Complications with Exoscope Use

The use of exoscopes in neurosurgery has been associated with positive surgical results and fewer cases of complications. Research showed that the percentage of cases where it was necessary to convert to using the operating microscope (OM) was very small because of problems such as distortion of images or technical problems. In most of them, however, the exoscope offered good-quality, clear visualization which resulted in better surgical accuracy, decreased surgical time, and shorter recovery time. The fact that there is a low switch rate to the OM and that the results as a whole are usually favorable can be taken as evidence of the efficacy of the exoscope in carrying out complex neurosurgical operations with low levels of complications.

Table 5: Surgical Outcomes and Complications with Exoscope Use

Study	Procedure Type	Complications Reported	Switching to OM	Outcomes
Montemurro et al. (2021)	Brain Surgery	None significant	3 cases of switch	Positive outcomes with enhanced visibility
Raheja et al. (2021)	Tumor Resection	Minimal	5% cases switched to OM	Reduced complications in cases with exoscope
Cardali et al. (2025)	Craniotomy	Some image distortion	1 case of switch	Faster recovery with exoscope
Vivek et al. (2025)	Spine Surgery	No major complications	2% switch rate	Reduced operative time and better precision

DISCUSSIONS

Exoscope has become an innovational technology in neurosurgical operations with massive benefits over the former operating microscope (OM). The exoscope is increasingly replacing the OM as it has greater imaging advantages and is more comfortable to operate due to ergonomic considerations when compared to the gold standard of visualization in neurosurgery. One of the highlights of the studies under review is that the exoscope is capable of providing better depth perception and providing high-quality 3D and 4K imaging, which are important in improving the accuracy of the surgery, especially when undertaking complex brain tumor resections and spinal surgeries (Montemurro et al., 2022). Surgeon burnout is also minimized by using the exoscope to offer a more comfortable operating experience, reducing the strain on the neck and back, which is often experienced at the fixed position of the OM (Ricciardi et al., 2019). This ergonomic advantage could be particularly helpful for such processes as long and complicated tasks, in which posture is crucial to reduce the effects of the long-term physical consequences (Siller et al., 2020).

The integration of exoscope into neurosurgery is also an indication that it has the potential of increasing the efficiency of workflow. The exoscope does not only allow shared visualization in real time to the entire surgical team as compared to the OM where a surgeon can only view what they are looking at in particular ways, but it also enables residents and the other team of surgical personnel to actively participate in the surgery (Ricciardi et al., 2019). This collaboration, in addition to the effectiveness of the teams, can help to make a decision faster, which can result in the reduction of working time, as well as in improved surgical outcomes (Fiani et al., 2021). In brain operations, in particular, the expanded scope and capacity to visualize detailed and high-definition images with the exoscope may result in more accurate excisions and reduced complications (Bin-Alamer et al., 2023). Research indicates that these features have a great impact on the final standards of surgical practice growth and lessening the possibility of reopera or complications (Vivek et al., 2025).

Nevertheless, although exoscope has very many benefits, there are challenges that are associated with its adoption. The most notable downside is that it is comparatively more expensive and more difficult to learn how to use it at the beginning (Teo et al., 2020). The large requirement to invest in the purchase and upkeep of exoscopes may become a serious obstacle particularly in resource limited environments. Moreover, the exoscope enhances the ergonomic nature of surgery, but the surgeons might have a hard time adapting at first, particularly during the shift to the new traditional OM (Haeren et al., 2022). The controls and visualization settings, as well as positioning of the device, have to be used by surgeons initially making this process sluggish (Steinhilber et al., 2023). Nevertheless, overcoming these difficulties, the exoscope can be identified as a promising device in the current neurosurgery, even with the reduction of the extent of fatigue and increased precision. The exoscope has yielded positive clinical outcomes, as far as clinical outcomes are concerned. The reduction in the number of complications and the rate of necessitation to revert to the OM because of technical or image distortion is constantly reported (Raheja et al., 2021). Where the switch was required, it happened due to minor problems such as image distortion or operative glitches, but not significant defects in the exoscope facility (Montemurro et al., 2021). The results of the present study are aligned with more general tendencies where exoscopes can help in improving the visibility of intricate structures to the surgeon, thereby minimizing the chances of mistakes. In addition, the necessity to depend on the OM is minimized, which translates into shorter recovery periods of patients, since the surgeries are conducted with fewer patients and with higher efficiency (Cardali et al., 2025). Although the exoscope is an interesting development that brings forth an improved way of visualizing the brain and its surroundings during neurosurgical procedures, its wide use will be reliant on addressing some of its challenges, including the cost and learning curve related to its application. Nevertheless, due to the advantages discussed in the literature survey, it is justified to believe that the exoscope is an excellent addition to the neurosurgical practice because of its benefits in ergonomics, surgical precision, and workflow efficiency. As more surgeons and institutions adhere to the exoscopes in their professional practice, the technology is likely to occupy an even more prominent place in the future of neurosurgery (Siller et al., 2020).

CONCLUSION

The present review shows that the exoscope has an increasing role in neurosurgery and that it greatly outperforms the conventional operating microscopes in the spheres of ergonomics, visualization, and outcome of surgery. The exoscopes strong features in making surgery-ingenious, surgeon less burnt out, and the sharing of real time image by everyone in the surgical team, have all been invaluable during the intricate surgery operations. Although the issues of high start-up expenses and learning curve are significant, the overall outcome in terms of surgeons improving precision, efficiency of workflow and patient recovery time justify its implementation. With the changes in technology, exoscope will introduce the possibility of turning out to be a pillar in the practice of neurosurgery; it will present significant advantages in patient wellbeing and surgical effectiveness. Implementation of this technology is likely to keep changing the way neurosurgical is conducted, making it more efficient and effective in the future.

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