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Comparative analysis of exoscope-assisted spine surgery versus operating microscope: A systematic review

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ABSTRACT

Background: Limitations in the operative microscope (OM)'s mobility and suboptimal ergonomics created the opportunity for the development of the exoscope. This systematic review aims to evaluate the advantages and disadvantages of exoscopes and OMs in spine surgery.
Methods: Following Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines, a systematic search was conducted in the major research databases. All studies evaluating the exoscopes and/or OMs in spinal procedures were included.
Results: There were 602 patients included in the 16 studies, with 539 spine surgery patients, 19 vascular cases, 1 neural pathology case, 19 cranial cases, and 24 tumor pathologies. When examining surgical outcomes with the exoscope, results were mixed. Compared to the OM, exoscope usage resulted in longer operative times in 7 studies, comparable times in 3 studies, and shorter operative times in 3 studies. Two studies found similar lengths of stay (LOS) for both tools, two reported longer LOS with exoscopes, and one indicated shorter hospital LOS with exoscopes. One study reported higher exoscope-related blood loss (EBL), but four other studies consistently showed reduced EBL. In terms of image quality, illumination, dynamic range, depth perception, ergonomics and cost-effectiveness, the exoscope was consistently rated superior, while findings across studies were mixed regarding the optical zoom ratio and mean scope adjustment (MSA). The learning curve for exoscope use was consistently reported as shorter in all studies.
Conclusion: Exoscopes present a viable alternative to OMs in spine surgery, offering multiple advantages, which supports their promising role in modern neurosurgical practice.

1. Introduction

Spine surgery underwent a critical technological advance when the operative microscope (OM) was the first used in the neurosurgical operating room. In 1977, Caspar and Yasargil performed an open microdiscectomy on the lumbar spine using a binocular system – the first visual instrument to magnify the surgeons' view.[1,2] The OM has become the gold standard in contemporary neurosurgical practice since that time, due to the improved operative field illumination and superior neuroanatomical visualization. Patient outcomes have been improved by decreasing tissue trauma and optimizing pathological resection and removal in various procedures.[3]

However, despite being a significant upgrade over no microscopic visualization, the OM faces several restrictions in terms of operative

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mobility. Surgeons are often forced into an uncomfortable posture, which can impact their musculoskeletal health, causing neck and back pain and reducing physician morale.[4–6] While recent advancements in minimally invasive surgery have ushered in an era of enhanced recovery for patients, they have also introduced the exoscope. Besides introducing a tubular retractor system along with angulated tools, exoscopes have a longer focal distance, provide a wider field of vision, and have demonstrated ergonomic benefits. Exoscopes can easily be positioned about 20 cm or farther above the operative field allowing for an unobstructed working space.[3,7,8]

With the increasing utilization of exoscope-assisted spine surgery, there is a need to assess the exoscope's comparative efficacy and safety against OM-assisted spine surgery. Therefore, this systematic review aims to compare exoscopes with OMs to determine the unique advantages and limitations of these systems to aid clinical decision-making and improve patient outcomes.

2. Methods

2.1. Search strategy and selection

This systematic review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines.[9] Online databases such as PubMed, Scopus, Google Scholar, and Cochrane CENTRAL were systematically searched from inception to the 14th of September, 2023. The following combinations of MeSH terms were used using the Boolean Logic:

"exoscope-assisted spine surgery", "exoscope", "exoscope surgery", "exoscope technique", "exoscope-guided spine surgery", "traditional operating microscope", "operating microscope", "microscope-assisted spine surgery", "microscope surgery", "microscopic spine surgery", "microscopic technique", "complications", "surgical outcome", "clinical outcome", "surgical complications", "postoperative complications", "intraoperative complications", "perioperative complications", "complication assessment", "complication evaluation".

2.2. Inclusion criterion

Studies that compared the exoscope with the OM and included perioperative complications in patients undergoing spinal surgery were included. Original studies including clinical trials, RCTs, cohorts, and case series were included.

2.3. Exclusion criterion

Review articles, books and documents, commentaries, and letters to the editor were excluded. Articles other than English language were also excluded.

2.4. Data extraction and quality assessment

The retrieved articles were initially reviewed by the two independent reviewers. They screened titles and abstracts and removed the duplicates using the EndNote 20 software. The extracted data was further verified by the reviewers. The third investigator was then consulted to address any discrepancies concerning the evaluation of studies. The study design, baseline characteristics, and various outcomes were extracted. For the quality assessment of the included studies, the Newcastle-Ottawa Quality Assessment Tool was used.[9,10]

2.5. Study definitions and endpoints

The primary outcomes of interest were mean operative time, mean length of stay, mean blood loss, surgical complications, learning curve assessment, optical quality, optical zoom ratio, mean scope adjustment, ease of use, dynamic range, depth perception, and cost.

3. Results

3.1. Literature search

The preliminary literature search yielded 133 results, which were screened by title and abstract. Sixteen studies met inclusion criteria following full-text review, consisting of a total of 602 patients. The search strategy is shown in Fig. 1. The quality assessment of the included studies is summarized in Figs. 2 and 3. Study characteristics and baseline characteristics of participants are provided in Tables 1–3.

3.2. Study characteristics

In the 16 studies, 602 patients were included, with various pathologies: spine ($n = 539$), tumor ($n = 24$), cranial ($n = 19$), vascular ($n = 19$), neural ($n = 1$). The pathologies that were operated on were degenerative spine pathologies, spinal canal pathologies disc herniations, vascular anastomoses, degenerative spinal myelopathies, epidural abscesses, spondylotic radiculopathies, gliomas, meningiomas, craniovertebral instability, and traumatic spinal cord compression. The procedures performed were lumbar decompressions, tubular discectomies, Transforaminal Lumbar Interbody Fusion (TLIF), oblique lateral interbody fusion (OLIF), end-to-side bypass procedures, tumour resections (intraneural schwannomas), anterior cervical discectomy and fusion (ACDF), microsutures and anastomoses of nerves, arteries, and veins, cervical corpectomy, cervical laminectomy, lumbar and cervical laminectomies, laminotomies, posterior decompression and fusion, microdiscectomy, and foraminotomy.

The exoscopes used were Video Telescope Operating Monitor (ViTOM), ViTOM mounted on mechanical holding arm, ViTOM 3D model TH200, Aeos Digital Exoscope, HD-XOscope, Mitaka Kestrel View II, 3D 4K-HD EX Sony Olympus, Synaptive BrightMatter Servo, and HD-2D Stereotactic Exoscope.

3.3. Surgical outcomes

3.3.1. Operative time

Among the 16 studies examined, the utilization of an exoscope was found to have varying impacts on operative times. In 6 of these studies, the operative times were observed to be longer when using an exoscope in comparison to the operating microscope. In 3 studies, the operative times were reported as comparable between the two tools, while in another 3 studies, the exoscope was associated with shorter operative times. Hafez et al.[11] conducted a study where they observed a statistically significant difference, with the exoscope resulting in an extended operative time of 9.2 min ($p = 0.004$). In contrast, Yao et al.[12] reported a significantly shorter operative time when employing the exoscope ($p < 0.05$).

3.3.2. Length of stay

Length of stay was comparable with the exoscope and OM in 2 studies.[13,14] In 2 studies,[15,16] LOS was observed to be longer when using an exoscope (9.71 ± 4.78 days) in comparison to the operating microscope (8.95 ± 4.11 days) while in another study,[6] the exoscope was associated with shorter LOS (5.9 ± 2.6 days) in comparison to OM procedures (7.3 ± 5.8 days).

3.3.3. Blood loss

Blood loss exhibited similar outcomes when comparing the utilization of an exoscope to that of an OM, as evidenced by Hafez et al.[11] Conversely, in a separate study by Siller et al,[6] it was observed that blood loss was higher (97 mL and 109 mL in ACDF and LPD groups respectively) when employing an exoscope as opposed to an OM. However, in four additional studies, the exoscope was consistently associated with reduced blood loss.[14–17]

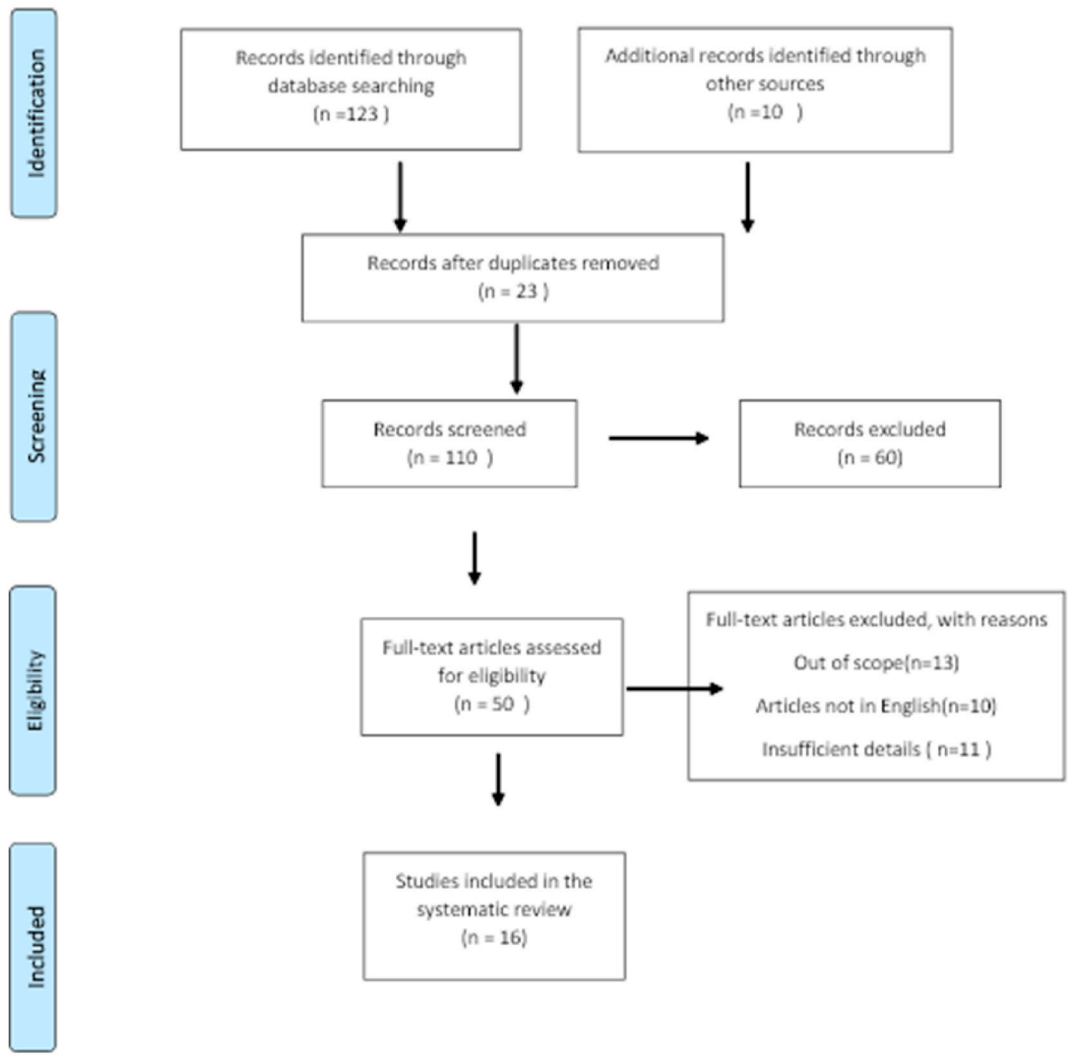

Fig. 1. PRISMA flowchart illustrating the study selection process.

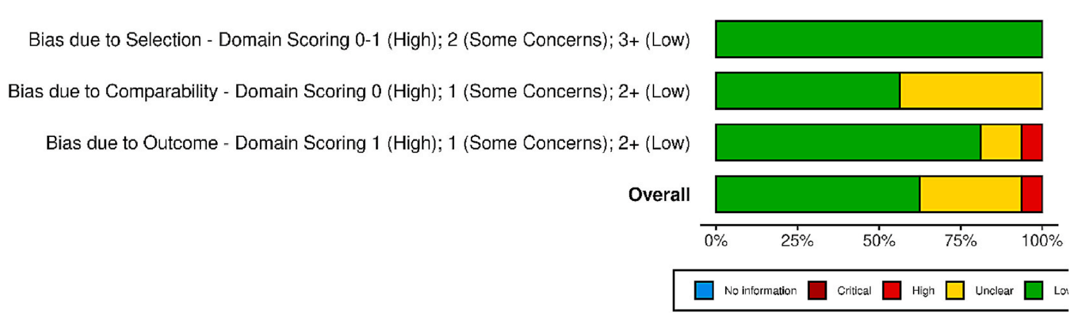

Fig. 2. Risk of bias assessment for each cohort study according to NOS. Plots created using the risk-of-bias visualization (robvis) tool.

3.3.4. *Various scores*

In the case of Yao et al.[12] the operating microscope resulted in higher Visual Analogue Scores (VAS) and lesser Neck Disability Index (NDI) scores. Siller et, al. shows greater clinical improvement (lesser NDI scores, higher Japanese Orthopedic Association (JOA) scores, and higher Oswestry Disability Index (ODI) scores) with the operating microscope in ACDF and LPD procedures. Lin et, al.[15] demonstrated slight improvements in JOA and VAS scores with the operating microscope in some cases. Ramirez et al.[14] showed decreased NDI scores with the operating microscope in minimally invasive TLIF.

3.4. *Comparison of specifications*

3.4.1. *Optical/image quality*

In most studies (7 out of 16), the exoscope was rated as superior in optical/image quality compared to the OM. Lin et al.[15] indicated that image quality with the operating microscope is comparable, but inferior in longer and deeper procedures. Conversely, two studies reported that the image quality of exoscope decreases with depth and is inferior to operating microscope.[14,16] While in 3 studies, image quality exhibited similar outcomes when comparing the utilization of an exoscope to that of an operating microscope[11,15,18]

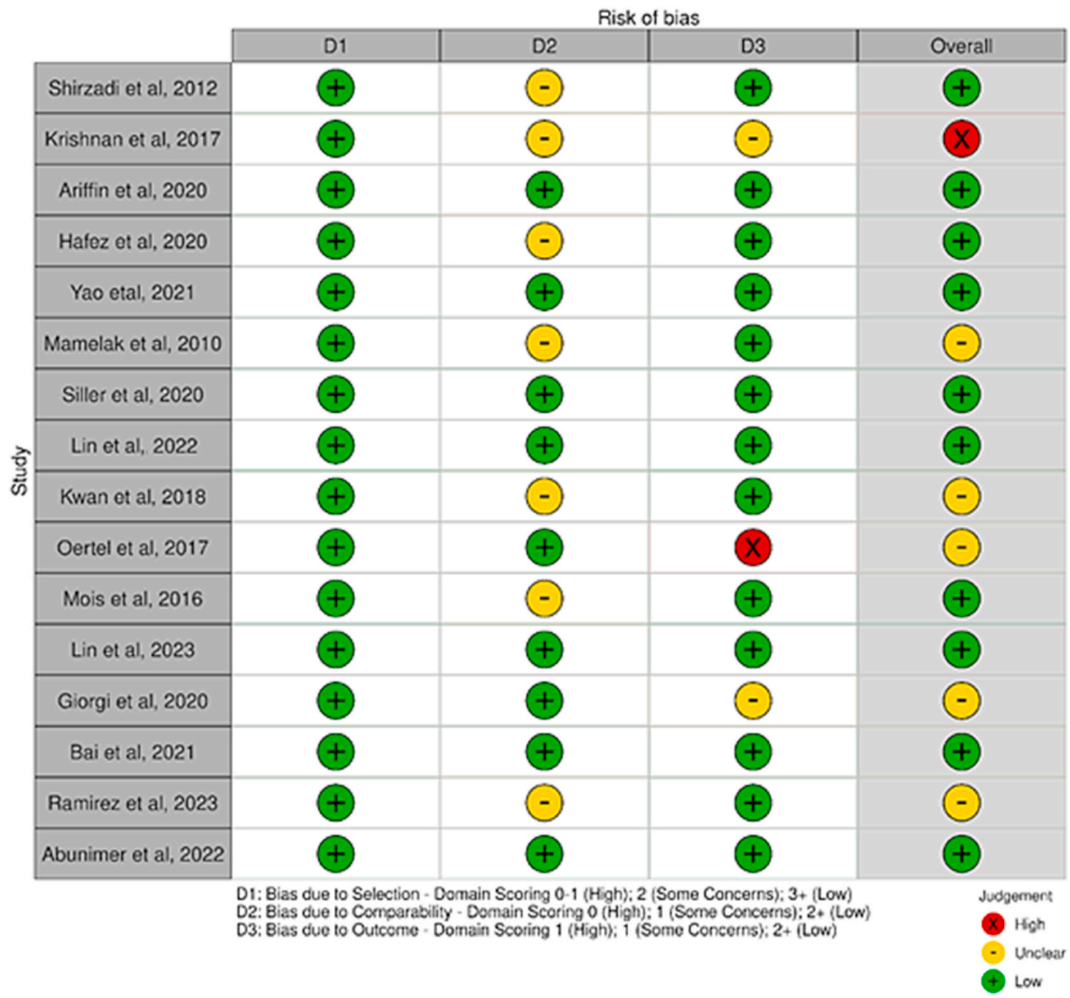

Fig. 3. Risk of bias assessment of cohort studies using Newcastle–Ottawa score. Plots created using the risk-of-bias visualization (robvis) tool.

3.4.2. *Illumination*

In 3 studies, the exoscope was rated as superior in illumination compared to the operating microscope.[11,19,20] Siller et al.[6] indicated that illumination in with the operating microscope is comparable. Conversely, 2 studies reported that illumination of exoscope is inferior to operating microscope.[8,16]

3.4.3. *Optical zoom ratio*

In certain instances where empirical data has been presented, discerning a definitive preference for one method over the other based on optical zoom ratio remains inconclusive. Across a corpus of four distinct research studies conducted by Hafez et al., Mamelak et al., Giorgi et al., and Kartik et al.[3,8,11,21] findings consistently suggest that the exoscope exhibits a superior optical zoom ratio in comparison to the conventional operating microscope. Contrastingly, Siller et al.'s[6] investigation deviate from this prevailing trend, as their analysis indicates that the exoscope yields an inferior optical zoom ratio when juxtaposed with the operating microscope. This counterpoint underscores the complexity of the comparative evaluation. In contrast to both the aforementioned trends, two additional studies[14,20] conducted by Oertel in 2023 and Ramirez et al. yield results indicating that the optical zoom ratio of the exoscope is on par with that of the traditional operating microscope.

3.4.4. *Mean scope adjustment (MSA)*

The mean scope adjustment was superior in exoscope as compared to the operating microscopes in 8 out of 16 studies. Siller et al.[6] indicated that MSA is inferior in exoscope as compared to OM. Conversely, 3 studies reported that the MSA of exoscope is comparable to the OM.[11,16,20]

3.4.5. *Ease of use and depth perception*

Ratings for ease of use and handling vary and are clearly indicative of more ease in handling the exoscope than the OM. Ariffin et, al., Bai et, al., and Abunimer et, al.[19,22,23] suggested the superiority of the exoscope due to its ergonomic benefits throughout the procedure. Hafez et, al., Lin et, al., and Mamelak et, al.[8,11,16] also noted increased freedom of movement for instruments under the exoscope. Conversely, Lin et, al.[15] reported unease in using 3D glasses with the exoscope. High dynamic range is found to be superior in exoscopes throughout the data shared by the studies. Depth perception is rated as superior with the exoscope in most cases. Lin et, al.[15] suggested that depth perception with the OM is superior in longer procedures with deeper areas. Surgeon discomfort is found to be less evident during the use of exoscope in most studies,[6,13,15,16,18,20,21] in comparison to the use of operating microscope.

Table 1
Baseline characteristics of study participants and pathologies.

Author et al	Year of publication	Number of participants	Pathology	Name of exoscope
Shirzadi et al	2012	48 [exo = 24; om = 24]	Degenerative Lumbar spinal pathology	Video Telescope Operating Monitor (VITOM)
Krishnan et al	2017	18	Lumbar and cervical spinal canal compression ($n = 5$); disc herniations ($n = 4$); anterior cervical dislocation ($n = 1$); intraneural schwannomas ($n = 2$); acute cerebellar hemorrhage ($n = 1$); parafalcine atypical cerebral hematoma caused by a dural arterio-venous fistula ($n = 1$); microsutures and anastomoses of a nerve ($n = 1$), an artery ($n = 1$), and veins ($n = 2$).	ViTOM® exoscope mounted on the mechanical holding arm
Ariffin et al	2020	74	Spinal canal pathologies	N/A
Hafez et al	2020	10 cases [exo = 5; om = 5]	Vascular anastomosis	Aeos Digital Exoscope
Yao et al	2021	48	Cervical spondylotic myelopathy	N/A
Mamelak et al	2010	16	Epidural abscess ($n = 1$), calcified disc ($n = 1$), herniated nucleus pulposus ($n = 3$), foraminal stenosis ($n = 1$), cranial pathologies[10]	HD-XOscope
Siller et al	2020	120 [exo = 60; om = 60]	Spinal pathologies	VITOM 3D model TH200
Lin et al	2022	50 [exo = 23; om = 27]	Cervical myelopathy	Mitaka Kestrel View II
Kwan et al	2019	10	Spinal Pathologies	3D 4K-HD EX (Sony Olympus Medical Solutions, Tokyo, Japan)
Oertel et al	2017	16	5 cranial and 11 spinal pathologies; Cervical canal stenosis C5–C6 ($n = 1$); Pseudarthrosis C2–C4 ($n = 1$); Intraspinal extradural angiolipoma Th12–L1 ($n = 1$); Lumbar canal stenosis L2–L5 with instability ($n = 1$); Lumbar canal stenosis L3–L4, nerve root scarring due to previous surgery L4–L5 ($n = 1$); Lumbar canal stenosis L4–L5, nerve root scarring due to previous procedure L3–L4 ($n = 1$); Disc herniation L4-L5 ($n = 2$); Disc herniation L5-S1 ($n = 1$)	3D-Vitom
Moisi et al	2017	6	Spinal pathologies	Synaptive BrightMatter Servo, Toronto, Canada
Lin et al	2023	90 [exo = 47; OM = 43]	Lumbar disc herniation	3D Exoscope
Giorgi et al	2022	20 [EX0 = 10; OM = 10]	Traumatic thoracolumbar spinal cord compression	HD 3D VITOM
Bai et al	2021	19	Spondylotic radiculopathy caused by bony foraminal stenosis	HD 3D Exoscope
Ramirez et al	2023	16 (EXO = 8; OM = 8)	Lumbar degenerative disc	N/A
Abunimer et al	2022	41	Spinal and Cranial Pathologies: Gliomas ($n = 11$) and meningiomas ($n = 7$), vascular pathologies ($n = 6$), metastatic tumors ($n = 2$), oligodendroglioma ($n = 1$), Langerhans histiocytosis ($n = 1$), and intracranial hemorrhage ($n = 1$); Spinal stenosis ($n = 8$), herniated disks ($n = 2$), cervicothoracic syrinx ($n = 1$), and craniovertebral instability with Chiari I malformation ($n = 1$)	HD-2D stereotactic exoscope

Table 2
Comparison of surgical outcomes between exoscope and operating microscope in different studies.

Study	Procedure	Operative Time		Length of Stay		Blood Loss		JOA Score		VAS Score		NDI Score		ODI Score	
		Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope
Shirzadi		longer	–	comparable	comparable	–	–	–	–	–	–	–	–	–	–
Krishnan		longer	–	–	–	–	–	–	–	–	–	–	–	–	–
Ariffin		–	–	–	–	–	–	–	–	–	–	–	–	–	–
Hafez	Bypass	longer	shorter	–	–	comparable	comparable	–	–	–	–	–	–	–	–
Ramirez		shorter	longer	comparable	comparable	–	–	–	–	–	–	–	–	–	–
Yao		shorter	longer	–	–	–	–	–	–	lesser	higher	–	–	–	–
Mamlek	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Siller	ACDF	longer	shorter	shorter	longer	greater	lesser	–	–	lesser	higher	comparable	comparable	comparable	comparable
	LPD	comparable	comparable	shorter	longer	–	–	–	–	–	–	–	–	–	–
Lin		comparable	comparable	longer	shorter	slightly lesser	slightly greater	improved ore	improved less	–	–	comparable	comparable	–	–
Kwan		longer	shorter	–	–	slightly lesser	slightly greater	–	–	–	–	–	–	–	–
Oertel		–	–	–	–	–	–	–	–	–	–	–	–	–	–
Moisi		comparable	comparable	–	–	–	–	–	–	–	–	–	–	–	–
Lin		longer	shorter	longer	shorter	slightly lesser	slightly greater	–	–	comparable	comparable	–	–	Improved comparably	improved comparably
Giorgi		shorter	longer	–	–	lesser	greater	–	–	–	–	–	–	–	–
Bai		–	–	–	–	–	–	–	–	–	–	–	–	–	–
Abunimer	cranial surgery	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	spinal surgery	–	–	–	–	–	–	–	–	–	–	–	–	–	–

3.4.6. Stereopsis, learning curve and cost-effectiveness

Stereopsis is rated as superior in exoscopes with the high dynamic-range cameras and 3D vision in most cases. However, Mamelak et al.[8] reported a lack of stereopsis in the complex procedure as the exoscope's major limitation. The exoscope demonstrated a shorter learning curve compared to the OM in all studies. The exoscope appears to be associated with lower costs compared to the operating microscope.

4. Discussion

4.1. Advantages of exoscopes over other microscopes

A complex picture is shown by 16 studies when comparing surgical results and technological advancements. The length of the operations varied; 6 studies[3,6,11,13,15,17] showed greater times with exoscopes, 3 studies[6,15,18] showed comparability, and 3 studies[12,14,21] suggested shorter periods. Blood loss and length of stay showed conflicting outcomes. Exoscopes were generally preferred in terms of optical and picture quality, however, certain investigations found depth limits. The superiority of illumination varies. Studies comparing optical zoom ratios produced contradictory findings, with some research endorsing exoscopes and others defending conventional microscopes. Lin et al.[15] evaluated the advantages and disadvantages of using high-definition 3D exoscopes versus binocular OMs in ACDF cases. While noting a slightly inferior visualization and image quality, it was reported that the exoscope is not only a safe alternative to OMs with improved ergonomics and stereotactic visual experience but also serves as a useful educational tool for the surgical team. Exoscopes were typically preferred because of their ease of use, depth perception, and affordability. Exoscopes often provided improved stereopsis, although there were certain drawbacks in more complicated surgeries, such as the inability to create a more precise line of site during deep dissections in some craniotomies.[8] Importantly, using an exoscope typically resulted in a reduced learning curve, which facilitated adoption by both residents and consultants.

Since the late 1960s, the surgical microscope has been a fundamental tool in neurosurgery, and it is still vital in the microsurgical treatment of brain and spine disorders.[24] Extracorporeal telescopes, colloquially referred to as exoscopes, are excellent substitutes to conventional OMs for surgical magnification due to advancements in digital imaging, wireless internet connection, screen technology, and optics.[25] In order to examine the target region while using the microscope, surgeons must look directly through the surgical microscopic objective lenses; however, it appears that this face-machine interface has been replaced by modern digital 3-dimensional (3D) imaging exoscopes.[26]

4.2. Visualization and comfort

In microsurgery and minimally invasive treatments, it has been extensively documented that the pursuit of extremely precise pictures and methods has been producing beneficial clinical outcomes and increasing patient satisfaction.[3,22,27,28] 3D glasses and 3D monitors have enabled surgeons to visualize important neural and vascular structures as well as tissue differentiation with high magnification. While a surgeon's posture is not restricted to the microscope's oculars, employing an exoscope has previously been associated with more mobility during surgery, higher levels of comfort, and less fatigue following lengthier procedures.[22,29,30]

4.3. Learning curve and adaptability

Exoscopes and other contemporary equipment need specialized training, however, the learning curve is quite short in comparison to traditional neurosurgery systems like operating microscopes (OM) and endoscopes.[6,13,27] With higher visual quality and more comfort for the surgeon, Muhammad et al.[28] reported cranial surgical outcomes that were equivalent to the OM. For surgeries involving the skull base, brain tumors, aneurysm clipping, vascular microanastomosis, and both cervical and lumbar complex spine, the exoscope system is a secure substitute for or a supplement to the already available binocular OM.[6,11,27,31–37] According to Siller et al.[6] there were no appreciable changes between patients who received lumbar posterior decompression (LPD) and anterior cervical discectomy and fusion (ACDF) surgery using an OM or an exoscope.[6]

4.4. Image quality and surgical productivity

Exoscopes are intended to give high-resolution 3D imaging of tissue structure, blood vessels, and other characteristics to enable more precise surgery and, by integrating a display video, to allow simultaneous surgical team watching. Exoscopes are the next generation of operational imaging because they allow the neurosurgeon to work while sitting more ergonomically, make it easier for the surgical team, and cut down on the amount of time surgeons spend looking at visuals via a microscope eyepiece. By fusing the endoscope's form factor with the microscope's image quality, these devices attempt to close the gap between OM and endoscopes.[18,38] The exoscope's ability to lower infection transmission to the surgical team during the COVID-19 pandemic was underlined by Ridge et al.[39] and Teo et al.[40] Exoscopic viewing has been shown to have certain drawbacks, particularly with early 2D exoscopes, such as limited utility in deep-seated cranial diseases, difficulty identifying hemorrhagic tissue, amplification of deep-seated pathologies, and most notably, a lack of stereopsis.[20,32] New 3D exoscopes appear to eliminate all of these drawbacks, however, they occasionally cause headaches and nausea owing to the usage of polarized glasses.[13,20,41] The shared 3D image that is available to everyone performing the surgery is a significant benefit of the exoscope.[11,42,43] By allowing surgeons to work simultaneously on the same monitor and exchange information with the surgical team, productivity is increased. Takahashi and colleagues[28] noted that assistant surgeons occasionally had a rotated image of the monitor, which can be resolved by using two or more 3D displays.

4.5. Quality and duration of suturing

In the largest comparison of the exoscope with the OM, Hafez and colleagues[11] demonstrated that both techniques are successful in performing bypass suturing.[15] However, the suturing duration was shorter when using the microscope, and the stitch distribution was better when using the exoscope. Gonen and colleagues[44] reported the largest series of exoscope-assisted glioma resections (56 patients), accounting for 44 cases of high-grade gliomas and 12 cases of low-grade gliomas and reporting just one (1.8%) perioperative complication (hemorrhage within the resection bed) in a patient with glioblastoma multiforme.

4.6. Operating time and complications

Up to 8% of postoperative surgical consequences include persistent motor deficiency.[44–47] In the largest series of patients to undergo transsphenoidal surgery for pituitary adenoma (239 patients), Rotermund et al.[42] reported that no serious episodes or minor complications based on the use of the exoscope occurred, as well as no significant differences regarding the duration of surgery, complications, or extent of resection compared to conventional microscopy. Ahmad et al.[25] reported 12 microvascular anastomoses in particular, showing no difference in operating time ($p = 0.714$), ischemia duration ($p = 0.972$), or microsurgical complications ($p = 1$) between the ORBEYE and traditional microscopy groups. In a prior assessment comparing exoscopes and microscopes for 3D visualization, Ricciardi et al.[48] concluded that the exoscope's picture quality, optical power, and magnification were at least on par with those of the microscope. To further investigate the surgical field and monitor bleeding, exoscopes equip surgeons with the ability to instantly transition between a micro to a macro vision.[41,47,49]

Exoscope use has been extensively documented, with a variety of

Table 3
Comparison of specifications between exoscope and operating microscope in different studies.

Author et al	Procedure	Optical/Image Quality		Illumination		Optical Zoom Ratio		Mean Scope Adjustment		Ease of use/ handling instrument/ holding arm
		Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope
Shirzadi		superior	inferior	–	–	–	–	–	–	superior
Krishnan		–	–	–	–	superior	inferior	superior	inferior	–
Ariffin		superior	inferior	–	–	–	–	–	–	superior
Hafez	Bypass	comparable	comparable	superior	inferior	superior	inferior	comparable	comparable	superior
Ramirez		superior	inferior	inferior	superior	comparable	comparable	superior	inferior	superior
Yao		–	–	–	–	–	–	–	–	–
Mamelak		superior	inferior	inferior	superior	superior	inferior	superior	inferior	superior
Siller	ACDF	superior	inferior	comparable	comparable	inferior	superior	inferior	superior	comparable
	LPD	superior	inferior	–	–	–	–	–	–	–
Lin		comparable but inferior in longer and deeper procedures	–	comparable but inferior in longer and deeper procedures	–	–	–	comparable	comparable	superior
Kwan		–	–	–	–	–	–	superior	inferior	–
Oertel		superior	inferior	superior	inferior	comparable	comparable	comparable	comparable	superior
Moisi		comparable	comparable	–	–	–	–	superior	inferior	superior
Lin		inferior	superior	inferior	superior	–	–	superior	inferior	superior
Giorgi		Superior	–	comparable	comparable	superior	inferior	superior	inferior	superior
Bai		–	–	superior	inferior	–	–	superior	inferior	superior
Ramirez	Minimally invasive TLIF	–	–	comparable	comparable	comparable	comparable	inferior	superior	comparable
	Open TLIF	–	–	–	–	–	–	–	–	–
Abunimer	cranial surgery	–	–	–	–	–	–	–	–	superior
	spinal surgery	–		–	–	–	–	–	–	–

exoscope types also being utilized in spinal surgery.[6,22,27,40,50,51] In a fascinating series of minor to large surgical spine operations performed on 69 patients using the exoscope, Ariffin et al.[22] reported only four incidences of dural rupture as surgical complications (or 5.8%), and no postoperative neurological impairments. The attending surgeon judged the comfort level of the surgeon's position intraoperatively as superior, particularly during "undercutting" procedures, and the intraoperative manipulation of the tools as equivalent to that of the OM.[22]

Exoscopes do, however, currently have certain limitations. According to Burkhardt et al.[50] who analyzed 16 cranial and 18 spinal surgical operations, switching to the OM was required in 5 out of 10 instances (or 50%) of cranial surgery due to the necessity for 5-ALA fluorescence-guided imaging in two cases and insufficient illumination of the depth of the operating field in 3 cases.

4.7. Limitations

No previous reviews exist for direct comparison with our systematic review, indicating a potential publication bias as only published data were considered. While our study is the first to systematically examine the comparative analysis of exoscope-assisted spine surgery versus operating microscope, a limitation arises from the absence of numerical data in the included studies, impeding a comprehensive quantitative comparison. Furthermore, the studies we incorporated, despite primarily targeting spine surgery cases, included a limited number of non-spine cases.

5. Conclusion

This systematic review provides a comprehensive comparison between exoscope-assisted spine surgery and traditional operating microscope-based procedures. While both technologies have their unique advantages and limitations, exoscopes exhibit superior ergonomics, shorter learning curves, and improved surgical efficiency. Despite challenges such as image quality and cost-effectiveness, exoscopes demonstrate potential for enhancing surgical outcomes and transforming the landscape of spine surgery. Future advancements addressing current limitations may further establish exoscopes as a valuable tool in neurosurgical practice.

Ethical approval

Not applicable as no patients are involved in this study.

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CRediT authorship contribution statement

Javed Iqbal: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Michael M. Covell:** Data curation, Writing - review & editing. **Sidra Jabeen:** Methodology, Writing -

Ease of use/handling instrument/ holding arm	High Dynamic Range		Surgeon's discomfort		Cost		Learning Curve	
Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope	Exoscope	Operating Microscope
inferior	superior	inferior	superior	inferior	less	more	comparable	comparable
–	–	–	–	–	–	–	–	–
inferior	superior	inferior	–	–	–	–	shorter	longer
inferior	–	–	–	–	–	–	shorter	longer
inferior	inferior	superior	–	–	less	more	shorter	longer
–	–	–	–	–	–	–	–	–
inferior	superior	inferior	–	–	–	–	shorter	longer
comparable	comparable	comparable	superior	inferior	less	more	shorter	longer
–	–	–	–	–	–	–	–	–
inferior	inferior	superior	superior	inferior	–	–	shorter	longer
–	–	–	–	–	–	–	shorter	longer
inferior	comparable	comparable	superior	inferior	less	more	–	–
inferior	–	–	superior	inferior	–	–	–	–
inferior	inferior	superior	superior	inferior			shorter	longer
inferior	superior	inferior	superior	inferior			shorter	longer
inferior	superior	inferior	–	–			–	–
comparable	–	–	comparable	comparable			Longer	shorter
–	–	–	–	–			–	–
inferior	superior	inferior	superior	inferior			shorter	longer
–	–	–	–	–			–	–

original draft. **Abdullah Nadeem:** Data curation, Validation, Writing - original draft. **Hamail Malik Gunjial:** Data curation, Methodology, Writing - original draft. **Hafiz Abdus Saboor:** Conceptualization, Data curation, Writing - original draft. **Aamir Amin:** Writing - original draft. **Yumna Salman:** Conceptualization, Data curation. **Muhammad Hassan Hafeez:** Conceptualization, Data curation, Writing - original draft. **Christian A. Bowers:** Conceptualization, Investigation, Project administration, Supervision, Validation, Writing - review & editing.

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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Abbreviations

OM: operative microscope
LOS: lengths of stay
EBL:: exoscope-related blood loss
MSA: mean scope adjustment
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis