Robotic Surgery in Neurosurgery: Current Applications and Comparative Evidence

Fabio Vinicius Barth[1], Melissa Maria Santos Volaco[2]

[1]State University of Ponta Grossa, School of Medicine, 4748 Av. General Carlos Cavalcanti, Ponta Grossa, Paraná, Brazil
Email: *fabiobarth00[at]gmail.com*

[2]Pontifical Catholic University of Paraná, School of Medicine, 1791 Imaculada Conceição, Curitiba, Paraná, Brazil
Email: *melissasantos8910[at]gmail.com*

Abstract: ***Robotic systems are increasingly used in neurosurgery, particularly in spine, functional, and selected cranial procedures, but their true advantage over conventional techniques remains under evaluation. This narrative review summarizes current robotic applications in spine instrumentation, deep brain stimulation (DBS), stereoelectroencephalography (SEEG), and skull base surgery, and synthesizes comparative data on accuracy, safety, workflow, and outcomes. In spine surgery, randomized trials and meta-analyses indicate that robot-assisted pedicle screw placement can improve or standardize accuracy and reduce radiation exposure, typically at the cost of longer setup times and higher financial expenditure. For DBS and SEEG, robotic platforms offer submillimetric targeting, shorter operative times, and efficient execution of complex multi-trajectory plans, with safety at least comparable to frame-based or manual techniques. Cranial and skull base applications remain largely exploratory, limited by instrument design and integration challenges. Overall, robotics provides enhanced precision, improved ergonomics, and support for minimally invasive strategies, while key limitations include cost, learning curve, and scarce clinical and economic evidence. Emerging advances in artificial intelligence, augmented reality, telerobotics, and haptic feedback suggest a future of more autonomous and personalized neurosurgical robotics, pending robust comparative and cost-effectiveness studies to justify widespread adoption.***

Keywords: Robotic neurosurgery; spine surgery; deep brain stimulation; stereoelectroencephalography; skull base surgery

1. Introduction

Robotic technology has already changed the way surgery is performed in areas such as urology, gynecology and general surgery, largely by enabling stable, minimally invasive procedures with improved visualization and refined instrument control. In neurosurgery, the adoption curve has been more cautious. The brain and spine impose demanding requirements in terms of accuracy and safety, and any new technology must integrate seamlessly with imaging, neuronavigation and neurophysiological monitoring.[1–5]

Even so, over the last decade robotics has moved from concept to clinical reality in several neurosurgical domains. Reviews focused on neurological applications consistently show that most clinical experience has concentrated on spine and functional procedures, particularly pedicle screw placement, DBS lead implantation and SEEG electrode placement.[1–6] More recently, interest has expanded to cranial and skull base surgery and to microvascular and microanastomotic tasks, although these applications are still in earlier phases of development.[7–12]

At the same time, a number of key questions remain open. For spine surgery, radiological accuracy is clearly improved or standardized with robotic guidance, but the influence on pain, function and reoperation rates is less well defined.[3,4] In DBS and SEEG, robotics appears to streamline planning and execution and maintains high targeting precision, yet comparative data on long-term neurological outcomes and quality of life are still limited.[5–9]

In this context, this article aims to provide a coherent narrative overview of robotic neurosurgery following the structure requested by the journal. We briefly review the background and literature, define the main clinical and methodological problems, describe our review approach, summarize key results and comparative evidence, and then discuss current limitations and future research directions.

2. Literature Survey

2.1 Evolution of robotic neurosurgery

Early neurosurgical robots were essentially stereotactic positioning devices, developed to assist with cranial procedures such as biopsies and functional surgeries. These systems were often combined with frame-based stereotaxy and, in some cases, augmented reality overlays for trajectory visualization.[5] With improved imaging, navigation and software, more sophisticated platforms emerged that could integrate preoperative CT or MRI data, plan trajectories in three dimensions and then guide instruments or drill sleeves along these paths.[1–4]

Lin et al. provided one of the most comprehensive overviews to date, describing the main robotic applications in brain and spine surgery.[1] According to their review, the bulk of clinical use has been in pedicle screw placement, stereotactic biopsies, DBS and SEEG, with skull base procedures representing a smaller but growing subgroup. Stumpo et al. and Singh et al. added a global perspective, showing that adoption is concentrated in high-resource settings and that there is considerable variability between centers in terms of indications, platforms and research output.[2,3]

2.2 Spine surgery

In spine surgery, robotic systems such as Mazor SpineAssist, Renaissance and TINAVI are typically used for pedicle screw placement, either in open or minimally invasive approaches. These platforms combine preoperative CT or intraoperative 3D imaging with planning software that defines screw trajectories. A robotic arm then guides the surgeon's instruments along these planned paths.[4]

Randomized controlled trials pooled by Li et al. suggest that robot-assisted pedicle screw placement improves or standardizes placement accuracy and reduces intraoperative fluoroscopy use versus freehand techniques.[4] Observational data and global experience support the idea that these benefits are most relevant in complex situations, such as deformity correction, multilevel fusions and revision surgery, where anatomy is distorted and visualization is more challenging.[2,3]

2.3 Functional neurosurgery: DBS

DBS represents another domain where robotic techniques have demonstrated increasing applicability. The procedure depends on placing electrodes within deep, small structures such as the subthalamic nucleus or globus pallidus internus with high precision. In the conventional workflow, a stereotactic frame is fixed to the patient's skull, imaging is obtained and trajectories are planned and executed using frame coordinates.

Robot-assisted DBS follows the same principle of image-based planning but replaces manual frame adjustments with a robotic arm that can move to the planned entry points and angles. Neudorfer et al. compared robot-assisted with frame-based DBS and reported that robots at least match, and in some cases improve, targeting accuracy, while reducing operative time and trajectory deviations.[6] Farah and Nuzzi & Brusasco, in broader reviews of neurosurgical and vision-related robotics, also highlight DBS as one of the most consolidated neurosurgical applications of robotics.[7,8]

2.4 Functional neurosurgery: SEEG

SEEG requires the placement of multiple depth electrodes to explore suspected epileptogenic networks. The number and complexity of trajectories make this procedure particularly suitable for robotic assistance. With robotic platforms, several parallel or converging trajectories can be planned simultaneously and then executed with high repeatability.

Abdallat et al. compared robot-assisted SEEG with manual frame-based techniques and found that robotic procedures allowed placement of more electrodes in less time, without increasing complications such as hemorrhage or infection.[9] Earlier narrative reviews by Farah and Nuzzi & Brusasco report similar findings, emphasizing that robots support complex implantation schemes that would be cumbersome or even impractical with manual techniques.[7,8]

2.5 Skull base and cranial surgery

The skull base is a demanding region for any surgical approach because of narrow corridors and the close relationship between tumors, vessels and critical neural structures. Robotic systems promise improved visualization, maneuverability and tremor filtration, but experience in neurosurgical skull base work is still relatively limited.

Pangal et al. systematically reviewed robotic and robot-assisted skull base neurosurgery and identified several types of procedures, particularly endoscopic endonasal and transoral approaches.[10] Ball et al. discussed cranial robotic applications more broadly, including biopsies, tumor resections and selected skull base operations.[11] Both reviews highlight the same main obstacles: current robotic instruments are relatively bulky and rigid, neurosurgery-specific wristed instruments are lacking, and integration with endoscopes and navigation is not yet ideal.[8,10,11]

2.6 Cross-cutting themes and external evidence

Outside neurosurgery, the robotic surgery literature provides additional context. Gamal et al. and Rahman et al. describe how robotic platforms have been used across multiple specialties, stressing common issues such as costs, learning curves and the need for clear indications.[15,16] Cannizzaro et al. focus on microanastomosis and supermicrosurgery, where precise motion scaling and tremor suppression are essential, and discuss how these robotic systems could be adapted for neurosurgical bypass and microvascular procedures.[12]

More conceptually, Bergholz et al. show that haptic feedback can improve performance in robot-assisted surgery, which has clear implications for delicate neurosurgical tasks.[13] Kim et al. demonstrate the feasibility of telerobotic neurovascular interventions using magnetically guided catheters, an approach that could ultimately expand access to advanced stroke and aneurysm care.[14] Finally, several authors have begun to explore AI-driven robotic workflows, both for direct clinical applications and for surgical education.[17–20]

3. Problem Definition

Although robotics is now present in many neurosurgical centers, several core questions remain unresolved. In practical terms, the main problems can be summarized as follows:

1) Clinical effect beyond technical accuracy

Most of the strongest neurosurgical data on robotics focus on technical outcomes such as screw placement accuracy or stereotactic error.[1–4,6–9] These metrics are important, but they are surrogate endpoints. The degree to which better radiological accuracy translates into improvements in pain, function, seizure freedom, quality of life or reduced reoperation rates is far less well established. Without these data, it is difficult to define when robotics offers a clinically meaningful advantage rather than just a technical refinement.

2) Cost-effectiveness and resource allocation

Robotic platforms require substantial capital investment and ongoing maintenance, and disposable components can add further expense.[2,3,16] At the same time, the potential economic benefits — fewer complications, fewer revisions, shorter length of stay, more efficient operating room use — have not been consistently quantified. This uncertainty complicates resource allocation decisions, especially in health systems with constrained budgets or in low- and middle-income countries.

3) Limited evidence in complex cranial and skull base surgery

For many cranial and skull base procedures, robotic use remains at the level of small case series and feasibility studies.[10,11] There are very few controlled comparisons with modern endoscopic or microsurgical techniques, and the available data do not yet support routine use. Defining the true added value of robotics in these demanding procedures will require more robust and systematic evaluation.

4) Training, learning curves and standardization

Robotic neurosurgery introduces new workflows and interfaces. Surgeons and teams must learn docking procedures, registration steps, and ways of resolving intraoperative discrepancies between plan and anatomy. Learning curves can be steep, and there is no universally accepted standard for training, credentialing or maintaining competence in robotic neurosurgery.[1–3,19,20]

5) Integration with AI, AR and telerobotics

Several promising technologies — including AI, augmented reality, telerobotics and advanced haptic systems — are already being tested in the surgical robotics field.[5,12–14,17–19] However, practical frameworks for incorporating them safely and ethically into daily neurosurgical practice, with clear lines of responsibility and robust validation, are still being developed.

4. Methodology / Approach

First, we identified relevant literature using electronic databases, primarily PubMed, as well as major publisher platforms. Search terms combined "robotic neurosurgery", "robot-assisted", "spine", "pedicle screw", "deep brain stimulation", "DBS", "stereoelectroencephalography", "SEEG", "skull base", "neurovascular", "telerobotics" and "artificial intelligence".

Second, we focused on studies published from 2017 onward, in order to capture contemporary robotic platforms and workflows. Earlier articles were included when they provided important technical or conceptual foundations. We considered randomized trials, cohort studies, comparative studies, systematic reviews and narrative reviews, as well as key conceptual papers on AI, haptic feedback and telerobotics.

Finally, studies were prioritized if they reported clinical or technical outcomes such as accuracy, complication rates, operative time, radiation exposure or workflow metrics; if they provided direct comparisons between robotic and non-robotic methods; or if they described emerging technologies with clear implications for neurosurgical robotics.

5. Results & Discussion

5.1 Spine Surgery

In the spine, the clearest signal in favor of robotics relates to pedicle screw placement. Across multiple randomized trials analyzed by Li et al., robot-assisted screws were more likely to be fully contained within the pedicle or have only minimal cortical breach, while also requiring fewer fluoroscopic images.[4] These differences are most relevant in anatomically challenging regions — thoracic levels, deformities and revisions — where freehand techniques are more error-prone.

From a workflow perspective, spine robots can make minimally invasive approaches more reproducible by allowing accurate placement of screws and rods through small incisions under indirect visualization.[2–4] However, these advantages come at the price of longer setup and registration times, especially during a center's initial experience. In some series, the net operative time for robotic cases remains equal to or slightly longer than conventional cases, although this tends to improve with familiarity.[3,4]

The impact on downstream outcomes is harder to measure. Some studies suggest fewer malposition-related revisions with robotics, but the evidence is not yet strong enough to conclude that all patients benefit equally.[2–4,16] At present, the technology seems particularly useful in complex deformity surgery, multilevel constructs and revision procedures, while its incremental value in simple, single-level cases is more debatable.

5.2 Deep brain stimulation

For DBS, the main technical endpoint is targeting accuracy, often measured as the distance between planned and actual electrode positions. Neudorfer et al. showed that robot-assisted DBS achieves at least the same, and in some instances better, targeting precision than conventional frame-based stereotaxy, with shorter operative times.[6] The ability of robotic arms to move reliably between multiple entry points and angles without manual frame adjustments simplifies surgery and may reduce fatigue.

Clinical outcomes after robotic DBS, such as improvements in motor scores and medication reductions, appear comparable to those seen with traditional methods in the limited data available.[6–8] While this indicates that robotics does not compromise therapeutic effectiveness, it also highlights that the main benefits at this stage are logistical and ergonomic rather than clearly superior clinical results. Long-term comparative studies with standardized outcome reporting will be important to clarify whether more subtle advantages emerge over time.

5.3 Stereoelectroencephalography

SEEG appears to benefit most directly from robotic precision due to its complexity. Planning tens of electrode trajectories in three dimensions and executing them with high fidelity is inherently complex when done manually. Robots are well suited to this task because they can follow each planned path with stable, repeatable movements.

Abdallat et al. found that robot-assisted SEEG made it possible to implant more electrodes in a shorter operative time, without increasing complication rates compared with manual frame-based methods.[9] Other series describe similarly favorable accuracy and safety profiles.[7,8] These findings are particularly relevant in modern epilepsy surgery, where comprehensive sampling of suspected epileptogenic networks is crucial for accurate localization and for deciding whether resection, ablation or neuromodulation is the best therapeutic strategy.

5.4 Skull base and cranial procedures

In contrast, the evidence base for cranial and skull base robotic neurosurgery is still relatively thin. Pangal et al. reviewed available cases and showed that robots have been used in endoscopic endonasal procedures, transoral approaches and lateral skull base operations.[10] Ball et al. reported on a broader set of cranial applications, including biopsies and tumor resections.[11]

Across these reports, surgeons often highlight improved visualization and the ability to manipulate instruments within confined spaces, especially when articulating wrists or multi-arm setups are available.[10,11] However, they also consistently note drawbacks such as large instrument profiles, limited range of motion for neurosurgical tasks, and the practical difficulty of integrating robots with existing endoscopes and navigation systems.[8,10,11]

As a result, robotics has not yet replaced modern endoscopic and microsurgical techniques for most skull base and cranial procedures. At this stage, it is better viewed as a complementary tool used in selected cases or in highly specialized centers, and as a testbed for future, more neurosurgery-specific platforms.

5.5 Cross-cutting benefits and limitations

When all neurosurgical applications are viewed together, a few themes emerge. On the positive side, robotics provides stable, tremor-free positioning and submillimetric reproducibility in DBS, SEEG and pedicle screw placement.[1–4,6–9] Ergonomically, working from a console with motion scaling and comfortable posture can reduce surgeon fatigue during long cases.[1,12,15] In the spine, reduced intraoperative fluoroscopy use benefits both patients and operating room staff.[3,4]

On the negative side, the financial barrier is substantial. Capital and maintenance costs are high, and the economic benefits are still based on assumptions and small series rather than large-scale data.[2,3,16] Learning curves must be managed carefully to avoid early inefficiencies and potential errors. The lack of tailored neurosurgical instruments and incomplete integration with other technologies can limit what robots can actually do once they are in the operating room.[8,10,11]

5.6 Emerging technologies and trends

Recent work points towards an evolution of neurosurgical robotics from purely mechanical guidance systems to integrated, intelligent platforms. Bergholz et al. demonstrated that haptic feedback can enhance performance and reduce errors in robot-assisted surgery, highlighting a path towards safer manipulation in delicate microneurosurgical tasks.[13] Cannizzaro et al. reviewed microanastomosis robots that may eventually enable more precise cerebral bypass surgery by combining motion scaling with tremor suppression.[12] Kim et al. showed that magnetic manipulation can be used for telerobotic neurovascular interventions, raising the possibility that complex endovascular procedures could one day be performed remotely, with potential implications for stroke care networks and access in underserved regions.[14]

At the same time, AI is increasingly being incorporated into the robotic ecosystem. Wah discussed AI-driven robotic oncology as a model for precision, personalization and outcome prediction in oncologic surgery.[17] Chan et al. detailed how robotic platforms are being used for head and neck tumors.[18] Knudsen et al. and Jorna et al. reviewed AI tools for intraoperative decision support, workflow optimization and education in robotic surgery.[19,20] These concepts could, in time, be applied directly to neurosurgical planning, risk stratification and training.

6. Conclusion

Robotic surgery has carved out a real, although still evolving, role within neurosurgery. The most consolidated indications are robot-assisted pedicle screw placement, DBS lead implantation and SEEG electrode insertion, where robotics improves or standardizes technical accuracy, supports complex trajectory planning and can reduce radiation exposure. In these domains, robots appear at least non-inferior, and often technically superior, to traditional methods.

However, the evidence that these technical gains translate into consistently better clinical outcomes and cost-effectiveness is still incomplete. For skull base and many cranial procedures, the technology remains at the exploratory stage, limited by instrumentation and integration constraints and by the lack of robust comparative data. High capital and operating costs, together with steep learning curves, further restrict widespread adoption.

Future developments are likely to involve the integration of AI, augmented reality, haptic feedback, microanastomotic systems and telerobotics which suggests that neurosurgical robots will become more autonomous, more connected to data and more tailored to specific tasks. To ensure that this evolution benefits patients and health systems, the neurosurgical community will need to generate high-quality comparative evidence, develop standardized training and credentialing pathways, and address ethical and regulatory challenges head-on.

7. Future Scope

Several lines of work appear particularly important for the next phase of robotic neurosurgery.

First, prospective multicenter studies comparing robotic and non-robotic approaches in spine, DBS, SEEG and skull base surgery should be designed with robust clinical endpoints, long follow-up and predefined economic analyses. Without these data, debates about indications and value will remain largely theoretical.

Second, more detailed cost-effectiveness assessments are needed. These should look beyond direct operative costs and include complications, revision surgery, length of stay, return to work and quality-adjusted life years, ideally stratified by indication and case complexity.[2,3,16]

Third, further technological development is required. This includes designing neurosurgery-specific wristed and micro-instruments, improving compatibility with neuronavigation and intraoperative imaging, and refining haptic feedback and motion scaling for microvascular and skull base work.[10–13]

Fourth, the integration of AI, AR and telerobotics should progress from proof-of-concept to carefully supervised clinical implementation. This will likely involve AI-assisted planning and trajectory optimization, intelligent alert systems for intraoperative error detection, and pilot programs for remote neurovascular interventions under strict regulatory oversight.[14,17–19]

Finally, standardized training curricula, competency benchmarks and ethical guidelines will be essential. Simulation-based training and the use of objective performance metrics may contribute to reducing the learning curve and enhance patient safety as more centers adopt robotic neurosurgery.[19,20]

References

[1] Lin T, Xie Q, Peng T, Zhao X, Chen D. The role of robotic surgery in neurological cases: A systematic review on brain and spine applications. Heliyon. 2023;9:e22523. https://doi.org/10.1016/j.heliyon.2023.e22523

[2] Stumpo V, Staartjes V, Klukowska A, Golahmadi A, Gadjradj P, Schröder M, et al. Global adoption of robotic technology into neurosurgical practice and research. Neurosurg Rev. 2020; 44: 2675–2687. https://doi.org/10.1007/s10143-020-01445-6

[3] Singh R, Wang K, Qureshi M, Rangel I, Brown N, Shahrestani S, et al. Robotics in neurosurgery: Current prevalence and future directions. Surg Neurol Int. 2022; 13:522. https://doi.org/10.25259/sni_522_2022

[4] Li H, Zhang R, Shen C. Accuracy of pedicle screw placement and clinical outcomes of robot-assisted technique versus conventional freehand technique in spine surgery from nine randomized controlled trials: A meta-analysis. Spine. 2020. https://doi.org/10.1097/BRS.0000000000003193

[5] Madhavan K, Kolcun J, Chieng L, Wang M. Augmented-reality integrated robotics in neurosurgery: Are we there yet? Neurosurg Focus. 2017;42(5): E3. https://doi.org/10.3171/2017.2.FOCUS177

[6] Neudorfer C, Hunsche S, Hellmich M, Majdoub E, Maarouf M. Comparative study of robot-assisted versus conventional frame-based deep brain stimulation stereotactic neurosurgery. Stereotact Funct Neurosurg. 2018; 96: 327–334. https://doi.org/10.1159/000494736

[7] Farah J. Robotic-assisted procedures in neurosurgery. Acta Neurochir (Wien). 2019; 161: 553. https://doi.org/10.1007/s00701-019-03809-4

[8] Nuzzi R, Brusasco L. State of the art of robotic surgery related to vision: brain and eye applications of newly available devices. Eye Brain. 2018; 10: 13–24. https://doi.org/10.2147/EB.S148644

[9] Abdallat M, Joswig H, Nazer A, Hammouri M, Parrent A, MacDougall K, et al. Robot-assisted versus manual frame-based stereoelectroencephalography. J Neurosurg. 2025;1–7. https://doi.org/10.3171/2025.1.JNS241118

[10] Pangal D, Cote D, Ruzevick J, Yarovinsky B, Kugener G, Wrobel B, et al. Robotic and robot-assisted skull base neurosurgery: systematic review of current applications and future directions. Neurosurg Focus. 2022;52(1):E15. https://doi.org/10.3171/2021.10.FOCUS21505

[11] Ball T, González-Martínez J, Zemmar A, Sweid A, Chandra S, Vansickle D, et al. Robotic applications in cranial neurosurgery: Current and future. Oper Neurosurg. 2021; 21: 371–379. https://doi.org/10.1093/ons/opab217

[12] Cannizzaro D, Scalise M, Zancanella C, Paulli S, Peron S, Stefini R. Comparative evaluation of major robotic systems in microanastomosis procedures: A systematic review of current capabilities and future potential. Brain Sci. 2024;14(12):1235. https://doi.org/10.3390/brainsci14121235

[13] Bergholz M, Ferle M, Weber B. The benefits of haptic feedback in robot-assisted surgery and their moderators: A meta-analysis. Sci Rep. 2023; 13:46641. https://doi.org/10.1038/s41598-023-46641-8

[14] Kim Y, Genevriere E, Harker P, Choe J, Balicki M, Regenhardt R, et al. Telerobotic neurovascular interventions with magnetic manipulation. Sci Robot. 2022;7: eabg9907. https://doi.org/10.1126/scirobotics.abg9907

[15] Gamal A, Moschovas M, Jaber A, Saikali S, Perera R, Headley C, et al. Clinical applications of robotic surgery platforms: a comprehensive review. J Robot Surg. 2024;18(1):29. https://doi.org/10.1007/s11701-023-01815-4

[16] Rahman M, Bristi S, Yesmin T, Islam M. Application of robotics in modern surgery and critical operations: Current status, challenges, and future directions. INNOSC Theranostics Pharmacol Sci. 2025. https://doi.org/10.36922/itps.4664

[17] Wah J. AI-driven robotic surgery in oncology: advancing precision, personalization, and patient outcomes. J Robot Surg. 2025;19. https://doi.org/10.1007/s11701-025-02555-3

[18] Chan P, Wong E, Chan J. Robotic surgery for head and neck tumors: What are the current applications? Curr Oncol Rep. 2024; 26: 840–854. https://doi.org/10.1007/s11912-024-01546-1

[19] Knudsen J, Ghaffar U, R, Hung A. Clinical applications of artificial intelligence in robotic surgery. J Robot Surg. 2024;18. https://doi.org/10.1007/s11701-024-01867-0

[20] Jorna C, Margallo J, Margallo F. Artificial intelligence applications for learning in robotic surgery. Br J Surg. 2025. https://doi.org/10.1093/bjs/znae322.02