Robotic-Assisted Minimally Invasive Cranial Neurosurgery: Surgical Applications and Anatomy—A Systematic Review

Clarissa A.E. Gelmi[1], Giulio Cecchini[2], Francesco Di Biase[2], Pasquale De Bonis[1], Stefano Ratti[3]

Key words
- Keyhole approaches
- Minimally invasive neurosurgery
- Robotic neurosurgery
- Robotic platforms
- Skull base surgery
- Translational research

Abbreviations and Acronyms
DBS: Deep brain stimulation
DoF: Degree of freedom
TORS: Transoral robotic surgery

From the [1]Neurosurgery Unit, Translational Medicine Department, University of Ferrara, Ferrara, Italy; [2]Neurosurgery Unit, Regional Hospital San Carlo, Potenza, Italy; and [3]Cellular Signaling Laboratory, Anatomy Center, Department of Biomedical and Neuromotor Sciences (DIBINEM), University of Bologna, Bologna, Italy

To whom correspondence should be addressed:
Clarissa A. E. Gelmi, M.D.
[E-mail: glmcrs@unife.it]

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BACKGROUND: **The adoption of robotic systems in cranial neurosurgery remains limited, with most applications confined to stereotactic procedures. However, recent advancements in robotic engineering and the rise of minimally invasive neurosurgery have renewed interest in their transcranial and skull base applications. This systematic review analyzes current uses, technical limitations, and translational potential of robotic-assisted cranial neurosurgery.**

METHODS: **Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 guidelines, a systematic review of 3 databases was conducted. Eligible studies included robot-assisted cranial procedures (transcranial, transnasal, or transoral) beyond stereotactic navigation or endoscope-holding. Exclusion criteria comprised spinal, peripheral nerve, and purely endoscopic or non-neurosurgical interventions. Extracted data included study type, robotic platform, approach, and outcomes.**

RESULTS: **Twenty-seven studies (2002—2025) met inclusion criteria: 19 preclinical, 6 clinical, and 2 translational. Most preclinical studies used human donor heads or synthetic phantoms to simulate transnasal or transcranial robotic access. Clinical reports included skull base resections, third ventriculostomy, orbital tumor surgery, and microvascular anastomosis. The da Vinci system was most commonly used, while platforms like NeuRobot, Concentric Tube Robots, and SmartArm offered superior dexterity in confined spaces. Despite limitations such as bulk and lack of haptics, early clinical data support feasibility for robotic-assisted keyhole and skull base cranial procedures.**

CONCLUSIONS: **Robotics holds promise for minimally invasive cranial neurosurgery, but current systems are suboptimal for keyhole access. Targeted translational studies are needed to refine robotic design, optimize trajectory compatibility, and evaluate materials suited to cranial microsurgical demands. Future developments should focus on miniaturized, neuronavigation-compatible platforms tailored for high-precision intracranial manipulation.**

INTRODUCTION

Over the past 2 decades, the advent of robotic systems, initially revolutionizing general surgery, gynecology, and urology by providing 3D visualization, motion scaling, tremor filtration, and enhanced dexterity in confined spaces,[1] has progressively extended to specialties with narrower and deeper corridors, such as head and neck surgery.[2]

In cranial neurosurgery, however, the current use of robotics remains largely restricted to stereotactic frame-based procedures such as deep brain stimulation (DBS), stereo-electroencephalography, and stereotactic biopsies. In these settings, robotic systems, including *Renishaw Neuroinspire*, *ROSA Brain*, and *BEAR system*, act as high-precision trajectory holders, enabling submillimetric accuracy in target localization without engaging in active surgical manipulation.[3-5]

By contrast, the integration of robotic assistance into manipulative transcranial neurosurgery is still in its early stages. The complex three-dimensional anatomy and constrained operative field of the cranial vault present significant ergonomic and technological challenges.[6,7]

Most commercially available robotic platforms are not designed to accommodate the spatial limitations of keyhole cranial approaches,[8] leading to a persistent disconnect between the conceptual advantages of robotics and their practical applicability in neurosurgical procedures.

At the same time, the widespread adoption of minimally invasive cranial approaches, including supraorbital, mini-pterional, and retrosigmoid keyhole craniotomies, has underscored the utility of endoscopic visualization to achieve optical magnification[9] and has exposed the urgent need for robotic instrumentation specifically suited for precise manipulation within narrow intracranial corridors. This review aims to systematically evaluate the current literature on robotic-assisted minimally invasive cranial neurosurgery, focusing on transcranial, transnasal, and transoral procedures that go beyond trajectory planning. We review surgical feasibility, technical limitations, early outcomes, and ergonomics to guide future robotic platform development and translational research in minimally invasive cranial neurosurgery.

MATERIAL AND METHODS

A systematic literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 guidelines (**Figure 1**), with the objective of identifying studies on the application of robotic systems in cranial neurosurgery. The search was performed using PubMed, Web of Science, and EMBASE, without restrictions on publication date.

A structured query was constructed using a combination of medical subject headings and free-text terms related to neurosurgery and robotics. The search strategy included keywords such as *"neurosurgery," "neurosurgical procedures," "cranial surgery,"* and *"skull base,"* intersected with *"robotics," "robot-assisted surgery,"* and *"robotic surgery."* To enhance specificity, studies were excluded if they involved stereotactic procedures (e.g., DBS), endoscopic or exoscopic approaches, spinal surgery, radiosurgery, or non-neurosurgical specialties, including urology, gynecology, gastrointestinal, and cardiothoracic surgery. Equivalent queries were adapted for Web of Science and EMBASE. This systematic review was registered in the international prospective register of systematic reviews database (name and registration number: ID 1112499).

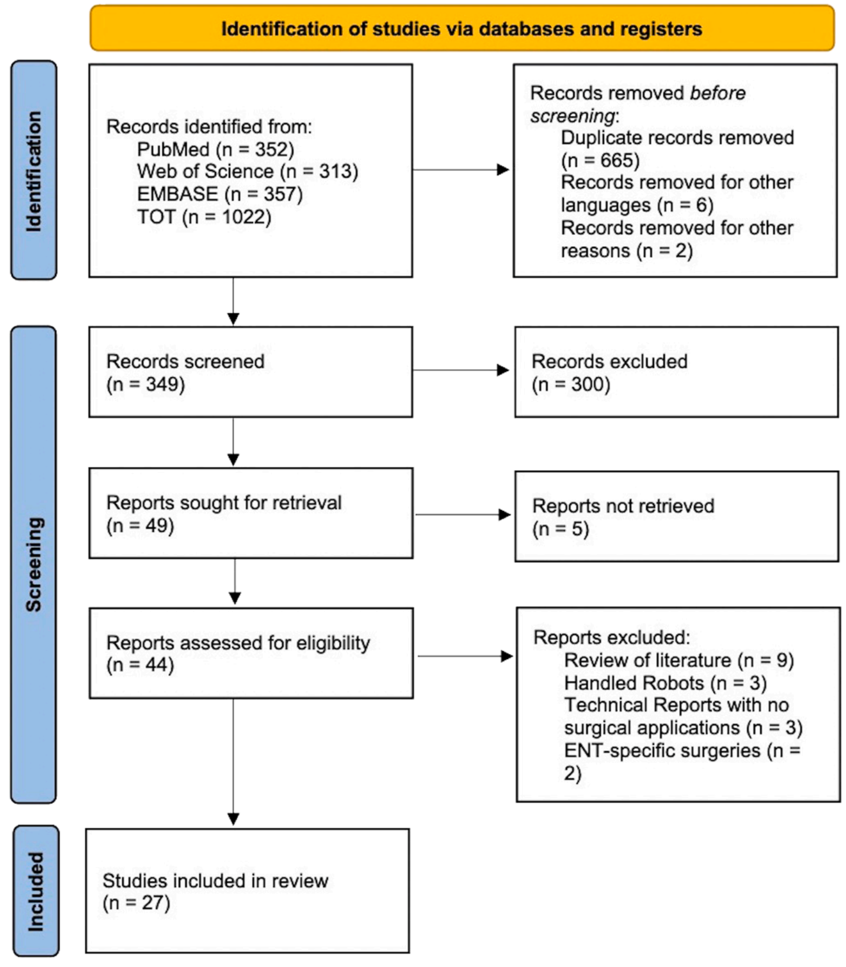

Figure 1. PRISMA 2020 flow diagram. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses, TOT, total; ENT, ear-nose-throat.

Inclusion and Exclusion Criteria

Studies were included if they described robotic-assisted procedures involving cranial or skull base access in humans, cadaveric donors, animals, or phantoms, employing robotic systems for active manipulation rather than mere navigation or endoscope holding. Only peer-reviewed articles in English were considered.

Exclusion criteria comprised stereotactic and frame-based applications (e.g., DBS, stereo-electroencephalography, and biopsies), spinal or peripheral nerve surgery, purely endoscopic or exoscopic procedures, and studies where robots served only as passive holders. Reviews, editorials, letters, and conference abstracts were also excluded, except when cited for discussion purposes.

Study Selection and Data Extraction

Titles and abstracts were independently screened, and the full texts of potentially eligible studies were retrieved for detailed assessment. Data extraction was performed using a structured spreadsheet (Microsoft Excel 2023 [Microsoft Corporation, Redmond, Washington, USA]), capturing the following variables: first author, title, journal, year of publication, study design, number of patients or specimens included, robotic platform employed, surgical approach adopted, study objectives, and main conclusions.

Risk of Bias and Quality Assessment

Given the methodological heterogeneity and predominantly preclinical nature of the included studies, neither quantitative meta-analysis nor formal risk-of-bias assessment was performed. Instead, the review emphasizes a qualitative synthesis focusing on surgical feasibility, procedural ergonomics, and the applicability of various robotic platforms across different cranial anatomical corridors in neurosurgical practice.

Table 1. Summary of Included Studies by Surgical Approach, Robotic Platform, and Clinical Indication

	Author	Year	Surgical Approaches	Robot
Oncological	Hongo et al.	2002	Intraventricular transfrontal, pterional, and interhemispheric approach	NeuRobot
	Takasuna et al.	2012	Intraventricular transfrontal	NeuRobot
	Marcus et al.	2015	Supraorbital Subfrontal, Retrosigmoid, and Supracerebellar-Infratentorial approach	Da Vinci
	Lee et al.	2024	Retrosigmoid, Supracerebellar-Infratentorial, and posterior occipitocervical junction approach	Da Vinci Xi
Skull base	Goto et al.	2003	Fronto-temporal approach	NeuRobot
	Hanna et al.	2007	Transantral approach	Da Vinci
	O'Malley and Weinstein	2007	TORS and c-TORS	Da Vinci
	Kupferman et al.	2009	Transantral approach	Da Vinci
	Lee et al.	2010	TORS	Da Vinci
	Dallan et al.	2012	c-TORS and EEA	Da Vinci
	Carrau et al.	2013	TORS and EEA	Da Vinci S
	Bly et al.	2013	Transorbital and EEA	Da Vinci
	Blanco and Boahene	2013	EEA and transmaxillary approach	Da Vinci Si
	Burgner et al.	2013	EEA	Concentric Tube Continuum Robots
	Hong et al.	2013	Supraorbital approach	Da Vinci
	Sreenath et al.	2014	TORS and EEA	Da Vinci
	Chauvet et al.	2014	TORS	Da Vinci S
	Fernandez-Nogueras et al.	2014	TORS	Da Vinci
	Swaney et al.	2015	EEA	Concentric Tube Continuum Robots
	Wirz et al.	2015	EEA	Concentric Tube Continuum Robots
	Chauvet et al.	2016	TORS	Da Vinci
	Marinho et al.	2019	EEA	SmartArm
	Henry et al.	2019	TORS with transpalatal access	Da Vinci
	Faulkner et al.	2020	Transorbital and EEA	Versius Surgical Robot System
	Mohsan et al.	2023	Transorbital	Da Vinci Xi
Vascular	Muto et al.	2024	Anastomosis MCA-Radial artery-ICA	Da Vinci Xi
	Watson et al.	2025	Microsurgical anastomosis	Symani

ICA, internal carotid artery; TORS, transoral robotic surgery; EEA, endoscopic endonasal approach; c-TORS, cervical transoral robotic surgery; MCA, middle cerebral artery.

RESULTS

Study Design and Experimental Models

A total of 27 studies, published between 2002 and 2025, met the inclusion criteria and were included in this review. The majority were preclinical investigations ($n = 19$), of which seven employed fresh-frozen human donor heads, while the remaining utilized specimens fixed according to local protocols, most commonly in formalin or preserved with silicone injection and 95% ethanol immersion.

Five of these preclinical studies adopted synthetic phantoms to simulate robotic transnasal pituitary tumor resection, enabling trajectory testing and instrument manipulation in anatomically constrained models. Notably, 1 preclinical investigation extended the transoral robotic surgery (TORS) approach to live animal models, specifically using a mongrel dog to access the midline and anterior skull base.[10]

In 1 case, a preclinical human body donor study evaluating the combined endonasal endoscopic approach and TORS for skull base malignancies was subsequently translated into a clinical application, reporting 2 case reports involving extensive nasopharyngeal and skull base tumors managed through this

Table 2. Technical Specifications and Comparative Features of Robotic Platforms Applied to Cranial Neurosurgery

	Type of System	Controlled Mode	Arms	Visualization	Commercial/ Sperimental	Advantages	Disadvantages
Da Vinci	Master-slave teleoperated, multi-arm robotic platform	Dual-console system, motion scaling, tremor filtering	7 DoF endowrist instruments	Endoscope 3D HD immersive vision with a 12-mm-diameter camera of 0° and 30°.	Commercial	High dexterity, widely available, stable platform	Large footprint, limited compatibility with neurosurgical tools, lack of haptics
NeuRobot	Micromanipulator-slave teleoperated	Console interface with endoscopic integration	Rigid 10-mm-diameter and 17-cm-long arm with insertion cylinder for installing a 3D endoscope, 3 microinstruments with tip <1 mm, and 5 irrigation and suction channels. 3DoF (rotation, neck swinging, and forward/backward motion)	Endoscope 3D camera of 4 mm	Sperimental	Precise micromanipulation, minimal invasiveness	Lack of tactile sensitive feedback
Concentric Tube Continuum Robots	Continuum teleoperative Robot	Teleoperated via user interface (Phantom Omni)	Concentric precurved tube made by nitinol with 6 DoF. The tubes rotate and translate inside one another, creating a tentacle-like motion with diameters from 0.15 to 14 mm	External camera and software	Sperimental	High flexible, small diameter, suitable for narrow corridors	Limited force output, lacks clinical validation, no haptic feedback
Versius Surgical Robot System	Teleoperated modular robotic system	Open console, hand controllers with programmable foot pedals, motion scaling, tremor filtering	Two robotic arms with 5 mm surgical instruments with wristed angulation at the tip and 7 DoF	10 mm 3D Endoscope HD visualization	Commercial	Compact footprint, improved ergonomics, open-console communication, high instrument dexterity, and modular design	Lack of neurosurgical-specific instruments and haptic feedback, no integrated navigation or microscope compatibility
SmartArm	Master-slave robotic system	Master-slave and co-manipulation modes	Two industrial-type robotic arms with 3.5 mm-diameter flexible tools attached to its distal tip, with lengths from 100 to 300 mm and with 9 DoF	4 mm Endoscope	Sperimental	High-precision tools with a real-time collision-avoidance algorithm, promising for intracranial use and for surgeries in narrow corridors	Complex setup, not widely available, limited publications
Symani	Fixed joysticks connected to a framework and microsurgical instruments	Console connected to an ergonomic chair with a foot controller and 2 joysticks with motion scaling (up to 20:1) and tremor filtering.	7 DoF with articulated wristed microinstruments	3D visualization system or a conventional microscope	Commercial	High precision, control, and accuracy of robotic arms.	Absence of touch sensation. Not yet optimized for deep cranial corridors. Further improvements in the grip of the microinstruments are necessary.

DoF, degree of freedom; HD, high definition.

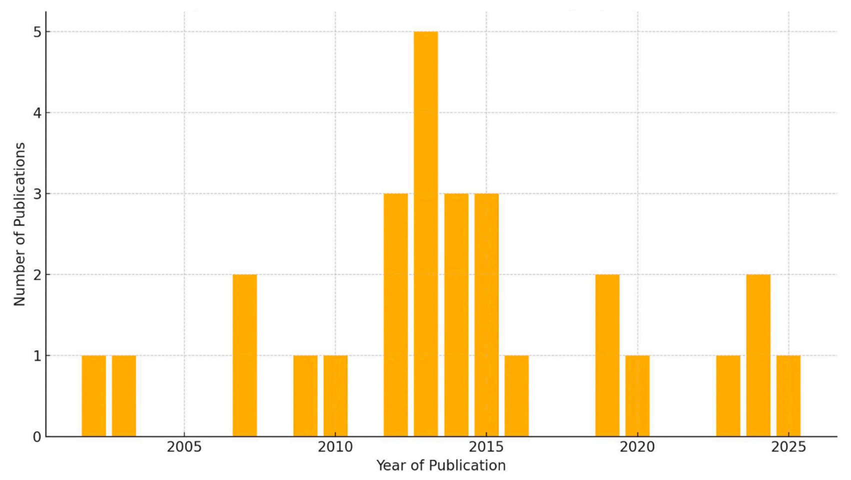

Figure 2. Temporal distribution of publications included in the literature review.

hybrid corridor.[1] Similarly, Takasuna et al.[11] simulated transventricular approaches in human donor heads, followed by a clinical application in a patient with obstructive hydrocephalus secondary to a midbrain venous angioma, who underwent a robotic third-ventriculostomy using the NeuRobot system.

In total, six clinical studies were identified. These include the following:

- A case report describing the use of NeuRobot for resection of a recurrent atypical meningioma of the left middle cranial fossa via a frontotemporal approach[12];
- Two case series, each involving 3 patients with skull base or nasopharyngeal pathologies: one[13] employed a combined endonasal endoscopic approach and TORS approach using the da Vinci system, while the other[14] utilized a transpalatal TORS corridor for clival chordomas, also with the da Vinci platform;
- A prospective study including 4 patients with sellar tumors treated via TORS with the da Vinci system[15];
- A pilot study assessing robotic-assisted orbital surgery in 4 patients with periocular tumors[16];
- A clinical study involving six patients undergoing robotic-assisted free flap scalp reconstruction with Symani, specifically for vascular microanastomosis.[17]

Surgical Approaches and Target Areas

The surgical approaches identified in this literature review were categorized according to their corresponding neurosurgical subspecialty, including oncological, skull base, and vascular procedures (Table 1).

- Four studies[8,11,18,19] described transcranial approaches, including transfrontal intraventricular routes for thalamic lesion biopsies, septostomy, or ventriculostomy, as well as pterional, interhemispheric, supraorbital subfrontal, retrosigmoid, supracerebellar-infratentorial, and posterior occipito-cervical junction approaches.
- Twenty-one articles focused on skull base approaches,[1,10-15,20-33] predominantly utilizing transnasal and transoral corridors. Variants included cervical TORS, transpalatal, transantral, and hybrid configurations combining endonasal endoscopy with transoral robotic instrumentation. These techniques primarily targeted the sellar, clival, and nasopharyngeal regions. Among these, only 3 studies[15,24,33], investigated the transorbital corridor, and one[27] the supraorbital route, aiming at lesions within the anterior cranial fossa, orbit, or parasellar area. Additionally, a single case report[12] described the use of a standard frontotemporal craniotomy for robotic-assisted resection of an atypical meningioma.
- Finally, 2 studies[16,34] evaluated the application of robotic systems in vascular neurosurgery, specifically for performing microvascular anastomosis.

Robotic Platforms

The da Vinci Surgical System (Intuitive Surgical, USA) was the most frequently employed robotic platform, cited in 18 studies (Table 2). It is a multi-arm, master-slave teleoperated system equipped with 7-degree of freedom (DoF) articulated endowrist instruments, 3D high definition stereoscopic endoscopy, motion scaling, and tremor filtration. Although originally developed for abdominal and pelvic surgery, it has been adapted in cranial neurosurgery for transoral and transnasal routes, yet remains limited by its large footprint, lack of neuronavigation integration, and absence of skull base-specific instruments.[7]

The NeuRobot, developed in Japan, consists of a compact rigid arm (10 mm diameter, 17 cm length) with 3 DoF, designed for intracranial micromanipulation through a stereoscopic endoscope and a console interface. Although used in both human body donors and clinical transventricular cases, its limitations in dexterity, scalability, and integration with image guidance systems ultimately prevented widespread adoption.[11,12,18]

The Concentric Tube Continuum Robot is an experimental system composed of precurved, telescopically nested nitinol tubes, allowing for 6 DoF depending on configuration. Controlled via a teleoperation interface, this platform excels in narrow, curved anatomical corridors such as transnasal and skull base routes and was tested in 3 preclinical studies using phantoms.[26,30,31] While highly maneuverable, it remains noncommercial and lacks haptic sensing and clinical validation.

The Versius Surgical System (CMR Surgical, UK) is a modular commercial platform with 7 DoF arms mounted on

Table 3. Experimental Applications of Robotic Systems in Keyhole Cranial Approaches: Instrumentation, Access, and Outcomes

	Robot	Surgical Instruments	Range of Movements	Specimens	Skin Incision	Approaches	Results	Advantages	Disadvantages
Hongo et al. (2002)	NeuRobot	Micromanipulator with external diameter of 10 mm and tip diameter of 1 mm, endoscopic 3D camera of 4 mm	3 DoF, swing of the neck between 0 and 90°, minimal movement is less than 20 μm/driving motor pulse.	Alcohol-fixed Human Cadaveric Head	Fronto-temporal	Trans-frontal intraventricular; pterional; interhemispheric	Third-ventriculostomy through a keyhole, arachnoid dissection of the Sylvian Fissure and exposure of the optic nerve and ICA, exposure of the optic chiasm and ACoA	Surgeons can remotely operate under visual 3D control. Excessive movements are stopped by the slave micromanipulators.	Lack of a tactile sensation feedback. Only 3 DoF for the range of movement.
Takasuna et al. (2012)	NeuRobot	Microinstruments with a tip <1 mm.	4 DoF, with 0.02 mm accuracy with steady operation	Fixed Human Cadaver Heads	Frontal	Trans-frontal intraventricular	Third-ventriculostomy, fenestration of the septum pellucidum, biopsy of the thalamus, biopsy of the choroidal plexus of the lateral ventricle	Higher degrees of safety and accuracy. This system can coagulate and divide tissue simultaneously using both the KTP laser and microforceps in 2 independent micromanipulators.	The maneuverability is limited by the large insertion cylinder of 10 mm and lack of movement. The rigid insertion cylinder does not allow the insertion angle to be changed once the cylinder enters the ventricle.
Hong et al. (2013)	da Vinci	Endo-wrist microinstruments of 8 and 5 mm. High-definition 3D visualization through 12 mm endoscopic camera with 0° and 30°	7 DoF and 90° of articulation	Fresh Human Cadaver Heads	Supraciliary	Supraorbital keyhole and subfrontal	Exposure of optic nerve, ICA, optic chiasm, and oculomotor nerve. Dissection of the Sylvian fissure and exposure of M1 and M2. Opening of the lamina terminalis and exposure of A1 and A2. Correct placement of an aneurysmatic clip with standard clip applier.	High-definition 3D stereoscopic visualization. Better control with increased accuracy and reduced tremor, and a high range of instrument motion.	The lack of a proper bone-cutting tool. An improper position of the robotic arms may increase the risk of arm collisions, which could interrupt the surgical procedure. Very expensive.
Marcus et al. (2015)	da Vinci	Endo-wrist microinstruments of 8 and 5 mm. High-definition 3D visualization through 12 mm endoscopic camera with 0° and 30°	7 DoF and 90° of articulation	Fresh Human Cadaver Heads	Corresponding linear skin incisions	Supraorbital keyhole, retrosigmoid, supracerebellar-infratentorial	Arachnoid dissection toward the deep cisterns. Inability to simultaneously pass the 12-mm endoscope and instruments through the keyhole craniotomy in any of the approaches performed.	Articulated instruments provide greater dexterity, giving also ergonomic advantages, motion scaling, and tremor filtering.	The instrument arms cannot be placed in parallel through the keyhole craniotomy. The lack of haptic feedback.

Lee et al. (2024)	da Vinci Xi	Endo-wrist microinstruments of 8 mm and a 10 mm jaw length. High-definition 3D visualization through 8 mm endoscopic camera with 0° and 30°	7 DoF and 90° of articulation	Silicone-injected human cadaver heads preserved in a 95% ethyl alcohol solution	Corresponding linear skin incisions	Paramedian Supracerebellar-Infratentorial, Retrosigmoid, and Occipito-Cervical junction.	Exposure of the deep cerebral veins and pineal region with an adequate surgical grade of freedom. The root exit zone of the facial nerve was barely visible, and a space for tools to access was not secured. Exposure of the medulla and adjacent nerves with a moderate surgical freedom. The minimum window size that could accommodate 1 camera and 1 tool was 3 cm.	Articulated robotic arms give motion scaling and tremor filtering, enhancing surgical precision, under high-definition 3D endoscopic visualization.	It is necessary to have a larger window than those used during endoscopic surgery because the camera and tool are too large to use together. The diameter of the tools used intracranially was larger than that of the endoscopic tools, so there were limits to manipulation.

ACoA, anterior communicating artery; DoF, degree of freedom; ICA, internal carotid artery; KTP, potassium titanyl phosphate.

independent bedside units, featuring 3D high definition visualization and console-based motion scaling. Despite its compact design and reuse-friendly instruments, its current instrument set is limited to general surgery and does not include tools suitable for cranial procedures. Moreover, it lacks haptic feedback and is not integrated with neurosurgical navigation or microscopes.[33]

The SmartArm is a research-stage robotic manipulator engineered for neurosurgical precision. It integrates force and torque sensors, high-resolution encoders, and 9 total DoF, allowing fine, multi-segmented control within microsurgical spaces. Its architecture supports both teleoperation and autonomous or comanipulated actions, and it is compatible with standard operative microscopes. The platform was developed to overcome the limitations of size, rigidity, and feedback in traditional systems.[32]

Finally, the Symani Surgical System is a dedicated microsurgical telemanipulator offering 7 DoF per arm with articulated wristed microinstruments and motion scaling up to 20:1. Operated under a traditional surgical microscope and without haptic feedback, it was applied in a clinical series for robotic-assisted scalp free flap reconstruction, demonstrating precise vascular microanastomosis capabilities.[17] Some robotic platforms discussed are not Food and Drug Administration-approved for cranial neurosurgical use and remain investigational.

Comparative Observations

A clear distinction exists between general-purpose commercial systems and platforms designed for cranial microsurgery. While da Vinci and Versius offer good ergonomics, 3D vision, and motion scaling, their bulk, lack of neurosurgical tools, and large footprint limit their use in keyhole surgery. In contrast, experimental systems like NeuRobot (3 DoF), Concentric Tube Robot (up to 6 DoF), and SmartArm (9 DoF) offer better miniaturization and dexterity for confined spaces. NeuRobot is outdated due to mechanical limits; the Concentric Tube Robot allows curved transnasal access but remains preclinical; SmartArm combines high DoF with force sensing, showing promise for microsurgical manipulation.

Although most systems are still preclinical, early clinical use of Symani for microanastomosis and da Vinci for skull base procedures supports robotic manipulation beyond trajectory guidance.

Temporal Distribution of Publication

The temporal analysis of included studies revealed a bimodal distribution in the scientific interest toward robotic-assisted cranial neurosurgery (Figure 2). Although initial reports over 2 decades ago were mostly conceptual, driven by technological curiosity or adaptation from other specialties, a first publication wave emerged between 2010 and 2015, focusing on feasibility, instrument control, and visualization using the da Vinci system for transoral and transnasal approaches in cadaveric models.

From 2019 onward, a second, more diversified phase began, marked by the development of dedicated robotic platforms aimed at overcoming limitations in bulk, rigidity, and cranial integration. This period also explored transorbital, supraorbital, and multiportal routes, reflecting a shift from system adaptation to true innovation.

DISCUSSION

Current Landscape of Robotic Cranial Neurosurgery

This systematic literature review highlights the growing but still limited application of robotic systems to minimally invasive cranial neurosurgery. Most published studies remain preclinical or use human body donors, with only six early clinical series. Robotic platforms, such as da Vinci, have been adapted for skull base and intracranial procedures, primarily through transoral, transnasal, and keyhole supra- and infra-tentorial routes. Feasibility studies have demonstrated acceptable instrument maneuverability, improved visualization, and potential for enhanced surgical precision in narrow anatomical corridors.[8,11,22,23,28]

However, in their current form, most robotic platforms were not designed for neurosurgery, and adaptation to cranial anatomy often reveals intrinsic limitations.

These include the bulk of instruments, lack of haptic feedback, absence of drilling capabilities, and limited compatibility with neuronavigation systems.[8]

Marcus et al.[8] demonstrate that use of the standard da Vinci robotic system in keyhole transcranial endoscope-assisted microsurgery is neither safe nor feasible. In order to overcome the narrow funnel effect generated from arms in close proximity and the steep angle of approach to the skull base, Bly et al.[24] suggested combined approaches such as transnasal and bilateral medial orbital ports for the camera and instruments, respectively.

Despite this, robotic systems have proven particularly promising in midline transnasal, transoral, and supraorbital keyhole approaches, providing adequate exposure with reduced manipulation of critical neurovascular structures.[10,20,27]

Robotic Applications in Minimally Invasive Keyhole Neurosurgery

Recent preclinical studies have explored the feasibility of applying robotic systems to keyhole cranial neurosurgery, including supraorbital, retrosigmoid, supracerebellar-infratentorial, and transfrontal intraventricular approaches (**Table 3**). The da Vinci platform, particularly the Si and Xi models, has been the most frequently investigated, showing that endo-wrist instruments can provide enhanced dexterity and stable articulation within limited surgical corridors. Articulated arms with 7 DoF and motion scaling have facilitated microsurgical tasks such as arachnoid dissection, vessel exposure, and fenestration of intraventricular structures, even under constrained anatomical conditions.[11,18,19,27]

However, multiple limitations have emerged. The bulk of the robotic arms, the lack of bone-cutting capabilities, and the requirement for a wider-than-desired skin incision have constrained the full translation of these systems into clinical practice.[8,19] Similarly, early applications of the NeuRobot system demonstrated the potential for robot-assisted third ventriculostomy via transfrontal access but were hindered by limited maneuverability and the absence of haptic feedback.[11,18]

Overall, while these results affirm the technical feasibility of robotic-assisted keyhole procedures, they also highlight the critical need for task-specific miniaturized platforms, ideally integrated with high-definition optics, navigation compatibility, dedicated cranial tools, and microsurgical instruments.[8,11,18,19,27]

Technological and Anatomical Constraints in Keyhole Cranial Approaches

Across the literature, a consistent limitation is the mismatch between current robotic systems and the confined anatomy of the anterior, middle, and posterior skull base.[32] Most platforms rely on multiple external arms requiring wide triangulation, which is difficult to achieve through natural orifices or mini-craniotomies. Instrument collision and insufficient reach to deep targets are frequently reported procedural challenges.[8,19,27]

Moreover, the absence of integrated drills or bone-cutting tools limits their effectiveness for skull base access,[27] often necessitating hybrid strategies that combine robotics with endoscopic or microscopic drilling.[1,8,13-15,22,25-29,33]

These technical shortcomings are compounded by the anatomical complexity of keyhole corridors. Transnasal approaches are constrained by deep, narrow access and proximity to vital structures, including the internal carotid arteries, optic apparatus, pituitary gland and stalk, and anterior cerebral circulation (A1 and anterior communicating artery). Extensions toward the cavernous sinus risk cranial nerve injury (III, V1, V2, and VI), while transpterygoid variants require identification of the vidian nerve. Supraorbital approaches demand cerebrospinal fluid release to minimize frontal lobe retraction, navigating near the olfactory nerve, internal carotid artery, optic and oculomotor nerves, and A1-anterior communicating artery-A2 complex. Minipterional routes offer limited exposure through reduced craniotomies, requiring Sylvian fissure dissection to access the internal carotid artery, M1—M2 bifurcation, and optic nerve. Retrosigmoid access involves cerebellar relaxation and exposure of neurovascular structures such as the superior petrosal vein, vertebral artery, and cranial nerves IV—XII, with extended variants reaching the internal auditory canal and Dorello's canal. These anatomical and technical constraints highlight the need for robotic systems with enhanced miniaturization, refined dexterity, and trajectory control tailored to narrow, high-risk intracranial spaces.

The Missing Sense: Lack of Haptic Feedback

A persistent limitation of current robotic systems is the lack of force feedback, or "haptics."[35] In cranial neurosurgery, tactile input is crucial for distinguishing tumor from brain tissue, assessing vessel tension, and identifying pia-arachnoid planes. Its absence can result in either overly cautious dissection or inadvertent tissue injury.[36] Visual cues such as tissue deformation or color change offer partial compensation but are inadequate near critical structures like the brainstem, cranial nerves, or vascular loops. Although research into force sensors, soft robotics, and vibrotactile or auditory augmentation is ongoing, these technologies remain in preclinical stages.[18,32]

Training, Reproducibility, and Translational Opportunities

A central theme emerging from this review is the need for structured translational validation. While human body donor simulations continue to serve as a cornerstone for feasibility assessments, their current implementation lacks procedural standardization. Comprehensive studies evaluating the steric footprint of robotic systems and the required instrument angulation and trajectory alignment based on specific intracranial targets are currently lacking in the literature.

In this context, human body donors represent an ideal experimental platform for testing robotic instrumentation in a safe and reproducible manner. Recent studies have demonstrated the feasibility of using reperfused and reventilated human body donors, such as in the SimLife model, for high-fidelity surgical training, potentially reducing the learning curve and enhancing the translational readiness of novel technologies.[37]

The learning curve associated with robotic cranial procedures remains an important consideration. Evidence from early clinical studies suggests that TORS approaches, particularly for skull base access, may be associated with a steep initial learning curve, requiring familiarity with both endoscopic anatomy and robotic coordination.[38] Similarly, Symani-assisted microsurgical anastomoses demonstrated prolonged operative times during early cases, reflecting a procedural learning trajectory.[39] In contrast, other reports describe a relatively shallow learning curve when using the da Vinci system for robotic microvascular tasks, particularly when surgeons had prior experience with robotic suturing techniques in other contexts.[34] These findings underscore the importance of prior robotic exposure, task-specific simulation, and iterative procedural refinement as core components of training paradigms.

Ultimately, robotics in neurosurgery should not be viewed as a substitute for conventional techniques but rather as a natural evolution of existing minimally invasive strategies, especially those leveraging fully endoscopic keyhole corridors.[9] As proposed by our group and others,[23] these approaches provide the ergonomic and conceptual foundation upon which robotic solutions can be constructed. Bridging the current translational gap will require a cycle of anatomical validation, technical adaptation, and clinical feedback, which together will define the future landscape of cranial robotic neurosurgery.

Toward Precision Medicine: Integrating Robotics and Artificial Intelligence

In robotic surgery, automation is increasingly investigated to reduce intraoperative variability and enhance surgical precision, to ensure more consistent technical performance and reduce fatigue during prolonged procedures.[17]

Selected repetitive tasks, such as bone drilling and microsuturing, may be standardized without diminishing the central role of the surgeon, who remains the active decision-maker. In parallel, artificial intelligence has been applied both in the preoperative phase, through trajectory planning and simulation models, and intraoperatively, where algorithms can assist with the recognition and labeling of neurovascular and parenchymal structures by integrating multimodal imaging for real-time orientation.[40] All these technologies are being developed to advance precision medicine, fostering surgical strategies tailored to individual anatomical and pathological characteristics, with the goal of reducing operative times, limiting anesthetic exposure, and minimizing the extent of cranial approaches. In this perspective, ongoing research in robotic neurosurgery and the integration of artificial intelligence represent a concrete step toward patient-specific surgery, progressing in parallel with the remarkable technological development of recent years.

CONCLUSIONS

Robotic-assisted cranial neurosurgery is an emerging field with promising yet limited clinical applications, especially in cranial neurosurgery. Current commercial systems are poorly suited for keyhole approaches due to their size, limited angulation, and lack of neurosurgical integration. Experimental platforms like SmartArm, Concentric Tube Robots, and NeuRobot offer potential solutions through enhanced dexterity and miniaturization but remain in early-stage testing.

Targeted translational research is needed to refine robotic design, optimize trajectories, and develop microsurgical-compatible materials. Progress will depend on anatomically informed, clinically validated engineering to meet the demands of keyhole cranial surgery and ensure reproducible, minimally invasive workflows.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Clarissa A.E. Gelmi: Writing – original draft, Data curation, Conceptualization. **Giulio Cecchini:** Methodology, Conceptualization. **Francesco Di Biase:** Validation, Supervision, Conceptualization. **Pasquale De Bonis:** Writing – review & editing, Validation. **Stefano Ratti:** Writing – review & editing, Validation, Supervision, Conceptualization.

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