Review Article

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Robot-Assisted Stereotaxy in Functional Neurosurgery: An Updated Narrative Review

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Introduction/Background: Robot-assisted stereotaxy is increasingly used in functional neurosurgery because many procedures rely on predefined linear trajectories and rigid skull registration. It is particularly relevant for stereoelectroencephalography (sEEG), deep brain stimulation (DBS), and laser interstitial thermal therapy (LITT). Pediatric use requires special attention to skull thickness, fixation, registration, anesthesia workflow, radiation exposure, and age-dependent anatomy.

Methods: We performed a narrative review of robotic applications in functional neurosurgery, emphasizing pediatric practice. PubMed, Web of Science, and Google Scholar were searched from inception to March 2025 using terms related to robotic and functional neurosurgery, pediatric neurosurgery, DBS, sEEG, LITT, robotic platforms, and artificial intelligence. English-language clinical studies, technical reports, reviews, and selected platform sources were included when addressing accuracy, safety, operative time, workflow, or pediatric applicability.

Review findings: Platforms such as Neuromate, ROSA, Micromate, RONNA G6, ExcelsiusGPS, Sinovation Sinobot X1, Stealth Autoguide, and Cirq have been applied to stereotactic functional procedures. Evidence suggests robotic workflows can achieve accuracy comparable to conventional techniques and may reduce operative time or surgeon fatigue in selected settings. Results vary by platform, registration method, indication, study design, and population. Pediatric evidence is strongest for sEEG in drug-resistant epilepsy, while DBS and LITT remain promising but less studied.

Conclusions: Robot-assisted stereotaxy may improve efficiency and precision in functional neurosurgery, especially for multiple or highly precise trajectories. Pediatric adoption requires careful consideration of age-specific anatomical and workflow factors. Further pediatric comparative studies are needed to define platform-specific accuracy, safety, efficiency, cost-effectiveness, and outcomes.

Keywords: Robotics, Functional Neurosurgery, Stereotaxy, Pediatric Neurosurgery, sEEG

INTRODUCTION

Neurosurgery first introduced a medical robot in 1985, but only recent technological breakthroughs have made robotics more accessible, especially in functional neurosurgery, which heavily relies on millimetric precision [1,2] and targets specific neural circuits to manage movement disorders, pain syndromes, epilepsy, and psychiatric conditions [3–7]. Potential advantages in functional neurosurgery include: better targeting accuracy, shorter procedure duration, and less surgeon fatigue in stereotactic procedures [8]. In Stereoelectroencephalography (sEEG), multiple electrodes are implanted and manual readjustments of coordinates may increase the risk of human error [9]. Cardinale et al. pioneered robotic sEEG, reporting lower localization errors and a reduced major complication rate (1.2% vs. 2.6%) compared with frame-based methods [10]. Over the past decade, several robotic systems have become available.

Pediatric functional neurosurgery presents specific challenges that make robot-assisted stereotaxy particularly relevant. Children undergoing sEEG, deep brain stimulation (DBS), or laser interstitial thermal therapy (LITT) often require accurate access to small or deep targets, and workflows that minimize invasiveness, operative time, and radiation exposure [11–13]. At the same time, pediatric patients introduce constraints that are less prominent in adult cohorts, including skull thickness, skull size, cranial fixation, prior craniotomies or cranial defects, age-dependent anatomy, and anesthesia considerations. Therefore, although much of the robotic stereotaxy literature is adult or mixed-age, its

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translation to pediatric neurosurgery requires separate discussion. This narrative review summarizes current robotic platforms used in functional stereotaxy, evaluates evidence for accuracy, safety, workflow, and operative efficiency, and highlights pediatric-specific applications and limitations relevant to contemporary pediatric neurosurgical practice.

MATERIALS AND METHODS

We pursued a narrative review to capture the breadth and evolving nature of robotic applications in functional neurosurgery, defined here as procedures such as DBS, sEEG, and LITT, with emphasis on pediatric applications. An iterative literature search was conducted in PubMed, Web of Science, and Google Scholar from database inception through March 2025 using keywords related to robotic neurosurgery, functional neurosurgery, pediatric neurosurgery, and artificial intelligence (AI). Search terms included combinations of: (“robot-assisted” OR “robotic” OR “robotic stereotaxy” OR “stereotactic robot”) AND (“functional neurosurgery” OR “deep brain stimulation” OR “DBS” OR “stereoelectroencephalography” OR “sEEG” OR “laser interstitial thermal therapy” OR “LITT”). A second pediatric-focused search used combinations of: (“pediatric” OR “paediatric” OR “child” OR “adolescent”) AND (“robot-assisted” OR “robotic”) AND (“sEEG” OR “DBS” OR “deep brain stimulation” OR “LITT” OR “laser ablation”). Additional platform-specific searches included “ROSA,” “Neuromate,” “Neurolocate,” “Micromate,” “iSYS,” “RONNA,” “ExcelsiusGPS,” “Sinovation,” “Sinobot,” “Stealth Autoguide,” and “Cirq.” Search terms were refined whenever new themes emerged.

We included English-language clinical studies, technical reports, reviews, and platform-specific reports addressing stereotactic robotic interventions, focusing on accuracy, operative duration, complication rates, workflow considerations, pediatric applicability, and AI-based enhancements. Adult or mixed-age studies were included when they provided relevant information on robotic platforms, stereotactic accuracy, safety, or workflow not otherwise available in pediatric cohorts. We excluded non-English publications lacking reliable translation, purely spine-focused robotics, conference abstracts without essential data, and work without clear clinical relevance to functional stereotaxy. Manufacturer and regulatory documents were used only to confirm platform specifications and were not treated as clinical evidence.

Guglielmo Iess and Joao Pedro Ponce screened titles and abstracts, reviewed relevant full texts, and performed thematic grouping of the included literature. Because this was a narrative review rather than a systematic review, we did not aim for exhaustive coverage or formal quantitative synthesis, but rather a critical synthesis of representative evidence. Thematic categories were derived from the main clinical applications and issues identified in the literature: DBS, sEEG, LITT, robotic platform characteristics, registration methods, accuracy, safety, operative time, workflow considerations, pediatric-specific considerations, and future directions. Findings were organized by major themes, highlighting both areas of consensus and ongoing debates, thereby offering an integrative perspective on robotics in functional neurosurgery.

RESULTS

The literature was organized into major themes including robotic platforms, registration methods, accuracy and safety outcomes, operative workflow, pediatric applications, and future directions. Pediatric-specific studies were prioritized when available, while adult or mixed-age studies were included when they provided relevant data not otherwise available in pediatric cohorts.

GENERAL PRINCIPLES OF ROBOTIC NEUROSURGERY

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Although neurosurgical robotics involves intricate engineering, three core principles stand out: an articulated arm design that mimics stereotactic frame-based geometry, degrees of freedom (DOF) representing the translational or rotational axes positioning the end-effector in three-dimensional space [14], and varied joint types (prismatic, hinge, screw, or spherical) (**Fig. 1)** that each offer unique benefits and complexities impacting reliability and maneuverability. Neurosurgical robotic systems are generally anchored using one of three approaches, each offering distinct advantages: 1) Floor-mounted systems are freestanding platforms that offer a broad range of motion and versatility, typically positioned adjacent to the operating table; 2) skull-mounted systems, by contrast, attach directly to the patient's head via a frame or clamp. Although this approach offers a stable reference relative to the skull, the assembly itself moves in conjunction with the head, and thus is not entirely rigid in the absolute sense; 3) table-mounted systems affix directly to the operating table, offering a compact footprint and improved integration into constrained surgical environments. Despite differences in anchoring, these systems generally follow a three-stage workflow [2,10]: (1) preoperative planning on MRI (often supplemented by CT) to define the best entry point and target; (2) registration to align the patient's intraoperative anatomy with the virtual plan; and (3) execution, where the arm is precisely positioned for instrument placement. Once the robotic arm is positioned, surgeons manually insert instruments through its holder in order to execute the various surgical steps.

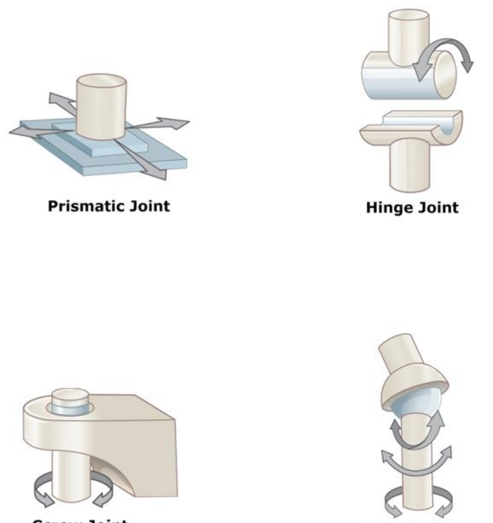

Figure 1. Illustrations of different types of surgical arm joints and their respective axes of rotation.

Although planning and execution are generally consistent across robotic platforms, the registration phase can differ significantly. Registration enables the software algorithm to recognize landmarks in the operative field that correspond with those in the imaging dataset. Broadly, two main categories of registration are used:

1. Fiducial Marker Registration (External Objects)

In this approach, distinct markers provide identifiable reference points for the software detection algorithm. These markers can be registered via intraoperative imaging (commonly using O-arm) to accurately align patient anatomy with the stereotactic plan [15-17]. This category also includes frame-based fiducial boxes or cages traditionally used in manual stereotactic workflows (e.g., CRW or Leksell frames).

2. Surface Matching (Inherent Patient Features)

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This method leverages the patient's natural skin contours. Earlier systems often employed laser-based point-cloud registration, scanning the head to produce a dense grid of spatial coordinates [15]. More recent platforms utilize 3D structured light, in which patterned beams (e.g., grids or stripes) are projected onto the scalp, capturing millions of data points within seconds and yielding highly detailed surface models (**Fig. 2)** [18,19].

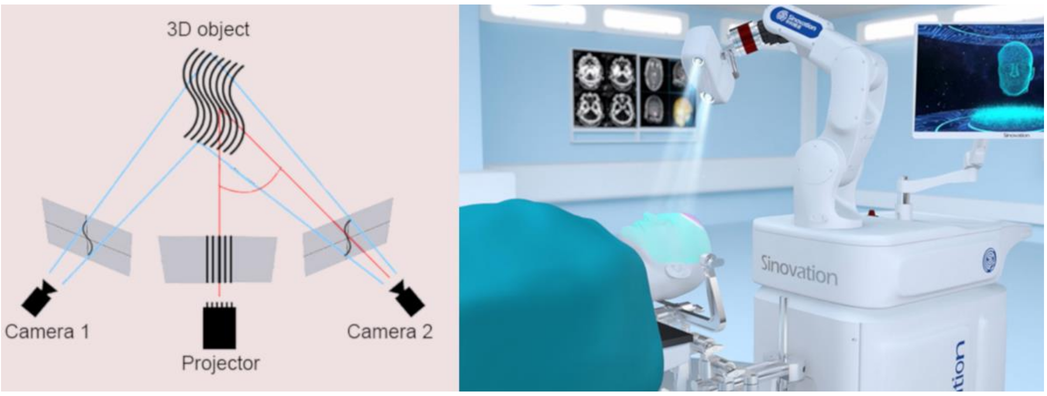

Figure 2. a) Sinovation Sinobot X1™ neurosurgical robot. Source: Sinovation Medical. b) Illustration of the three-dimensional structured-light system used by the Sinobot X1™. The cameras capture precise geometric data points based on deformation of the projected light pattern on the three-dimensional surface. Source: Hesam Hamidi.

By integrating either surface-based or fiducial marker registration, or a combination of both, modern robotic systems can robustly align the virtual plan with real-world anatomy. This alignment is critical for delivering the accuracy and reproducibility that robotic neurosurgery demands.

AVAILABLE COMMERCIAL ROBOTS

Although more than 20 neurosurgical robots have been tested [17–23], only eight have been applied to functional neurosurgery. Brief descriptions follow in chronological order, and more specific details on each can be found in Table 1.

Table 1. Overview of eight robotic platforms applied to functional neurosurgery, reporting degrees of freedom (DOF), mounting configuration, the procedure associated with the reported accuracy metric, representative accuracy values from the cited studies, frame-based or frameless compatibility, and principal registration technique. When only a single accuracy value is reported, the cited study provided target point error only. Because accuracy definitions and reported procedures displayed significant heterogeneity across studies, direct comparisons across platforms should be interpreted cautiously as representative values (rather than direct side-by-side evaluations).

Study	Robot	DOF	Procedure for accuracy metric	Corrected accuracy metric (mm, from cited study)	Other features
Vasconcellos et al. [28]	**Neuromate™** (Renishaw)	5	sEEG	**EPE/TPE**: 1.6/2.09	Floor-mounted; supports frameless & frame-based workflows; marker-based registration
Vasconcellos et al. [28]	**ROSA®** (Zimmer Biomet)	6	sEEG	**EPE/TPE**: 1.48/2.5	Floor-mounted; frameless; laser point-cloud or marker-based registration
Vasconcellos et al. [28]	**Micromate™** (iSYS)	4	sEEG	**TPE**: 1.61 (EPE not reported)	Table-mounted; frameless; marker-based registration
Raguž et al. [31]	**RONNA G6™** (Ronna Medical)	7	Cranial/DBS (data limited)	No published EPE/TPE values	Floor-mounted; frameless; marker-based registration
Anderson et al. [9]	**ExcelsiusGPS™** (Globus Medical)	6	Cranial stereotactic procedures	**TPE**: 1.9 (EPE not reported)	Floor-mounted; compatible with frameless & frame-based workflows; marker-based registration
Vasconcellos et al. [28]	**Sinobot X1™** (Sinovation Medical)	6	sEEG	**EPE/TPE**: 1.39/1.64	Skull-mounted; supports both frameless & frame-based workflows; uses 3D structured-light or marker-based registration
Atai et al. [38]	**Stealth Autoguide™** (Medtronic)	6	Cranial stereotactic procedures	**TPE**: 1.31 (EPE not reported)	Table-mounted; frameless; marker-based registration
Chesney et al. [39]	**Cirq™** (Brainlab)	6	sEEG / cranial	**EPE/TPE**: 1.4/2.6	Table-mounted; frameless; marker-based registration

EPE, entry point error; TPE, target point error.

1) Neuromate® (Renishaw): developed in 1987 and FDA-cleared in 1997, Neuromate was the earliest robotic system for stereotactic neurosurgery [10]. It supports both conventional stereotactic fiducial-based systems and frameless options **(Fig.3)**. Early reports suggested higher accuracy with its frame-based module [21], but later findings challenged this [22].

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2) ROSA® (Zimmer Biomet): FDA-approved in 2012 [24], ROSA is currently the most widely used commercial neurosurgical robot [28]. It exploits only frameless registration, performed with fiducials or laser facial scanning, and features integrated haptic feedback that lets surgeons intuitively guide the robotic arm.

Figure 3. Patient undergoing a sEEG procedure with a Neuromate® stereotactic neurosurgery robot.

3) Micromate™ (iSYS Medizintechnik GmbH): this compact platform represents the latest generation of the iSYS1 miniature robotic platform designed for needle biopsies and electrode insertion [26]. The system is grossly positioned via a multifunctional arm and then fine-tuned with remote joystick or automated control. Its smaller footprint differentiates it from traditional floor-mounted systems, though published data remain limited [29].

4) RONNA G6™ (Ronna Medical): the first RONNA model was introduced in 2015 in Croatia. This mobile, dual-arm system has been mainly evaluated for brain biopsies, although it can also perform electrode implantation [30,31].

5) ExcelsiusGPS™ (Globus Medical): launched in 2017, initially for spine surgery but adapted for cranial procedures in 2020 [32–34]. It incorporates force-sensing technology providing real-time feedback on deflections, a modular end effector for diverse neurosurgical tasks, and an integrated camera that tracks navigational arrays in real time.

6) Sinovation Sinobot X1™ (Sinovation) **(Fig.4)**: debuted in 2018, it also supports 3D structured light registration—often obviating the need for intraoperative CT [18,35,36]. An additional notable feature is its ability to operate in two modes—fully automatic or cooperative—providing flexibility based on surgical requirements.

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Figure 4. Patient undergoing a sEEG procedure with the Sinobot X1™ stereotactic neurosurgery robot. Source: Sinnovation Medical.

7) Stealth Autoguide™ (Medtronic) **(Fig. 5)**: a frameless, skull-mounted system that integrates with Medtronic's StealthStation. Cleared in 2019, it succeeded the Renaissance platform but features a very different, more compact design [37,38]. It employs real-time trajectory monitoring and marker-based registration for frameless workflows.

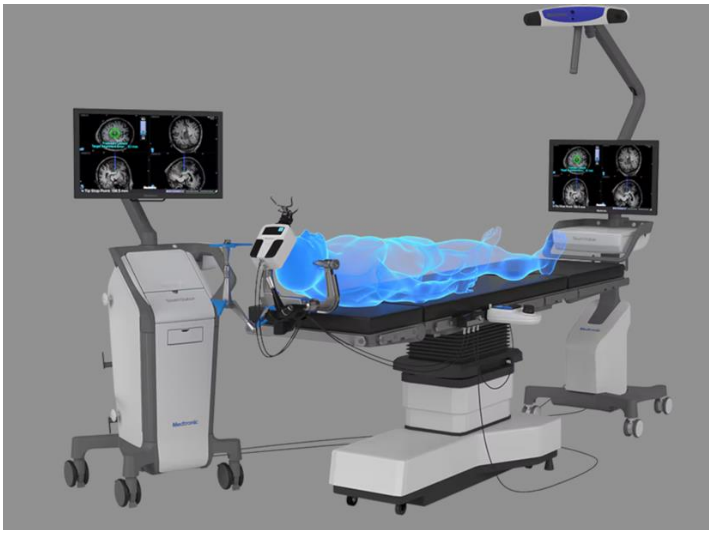

Figure 5. Digital model of a Stealth Autoguide™ neurosurgical robot (right) and the StealthStation™ surgical navigation system (left). Source: Medtronic.

8) Cirq™ (Brainlab): introduced in 2019, Cirq weighs only around 11 kg and relies on frameless registration [39]. It employs a semi-automated approach, allowing the surgeon to manually adjust the robotic arm to align with preplanned paths; once aligned, the arm locks into position to stabilize instruments.

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PEDIATRIC APPLICATIONS OF ROBOT-ASSISTED STEREOTAXY

Pediatric evidence for robot-assisted stereotaxy is most developed in drug-resistant epilepsy, particularly for sEEG. Robot-assisted sEEG may be useful in children because it permits multiple bilateral or multilobar trajectories through small incisions while avoiding large craniotomies and subdural grid exposure. McGovern et al. reported 57 children undergoing 64 robot-assisted sEEG procedures, with a definable epileptogenic zone in 89% of patients and one symptomatic hemorrhage with permanent neurological deficit [11]. Nelson et al. reported 19 children undergoing 23 ROSA-assisted epilepsy procedures, with 148 sEEG electrodes placed and no perioperative complications; ROSA was also used for laser probe insertion in five patients [40].

Beyond sEEG, pediatric robotic stereotaxy has been reported for DBS in childhood-onset dystonia and selected movement disorders [12,25]. Robot-assisted MRI-guided laser ablation has also been evaluated in children with epilepsy, with Lee et al. reporting pediatric laser-fiber placement accuracy data [13,41]. The pediatric literature remains concentrated around a limited number of platforms, especially ROSA. A pediatric comparison of ROSA and Stealth Autoguide in sEEG found both systems safe and reliable, with no procedural complications in 21 sequential pediatric implantations, although entry and target errors differed between systems [42]. Evidence for other platforms remains limited or largely extrapolated from adult and mixed-age studies.

Table 2. Representative pediatric studies of robot-assisted stereotaxy relevant to functional neurosurgery. Selected studies are organized by procedure and summarize the robotic platform, population, main findings, and relevance to pediatric functional neurosurgical practice. The table is intended as a descriptive synthesis rather than a direct comparison across platforms or indications. DBS, deep brain stimulation; EZ, epileptogenic zone; LITT, laser interstitial thermal therapy; ROSA, robotic stereotactic assistance; sEEG, stereoelectroencephalography.

Study	Procedure	Platform	Population	Main findings	Pediatric relevance
McGovern et al. [11]	sEEG	Robot-assisted	57 children, 64 procedures	EZ defined in 89%; one symptomatic hemorrhage with permanent deficit	Pediatric epilepsy-specific
Nelson et al. [40]	sEEG/LITT	ROSA	19 children, 23 procedures	148 electrodes; no perioperative complications; laser probe insertion in 5	Pediatric epilepsy workflow
Furlanetti et al. [12]	DBS	Robot-assisted	45 children with dystonia	Evaluated targeting accuracy in pediatric DBS	Pediatric DBS-specific
David et al. [25]	DBS	Neurolocate/Neuromate	Pediatric DBS	Reviewed frameless and frame-based robotic accuracy	Pediatric DBS platform-specific
Sickler et al. [42]	sEEG	ROSA vs Stealth Autoguide	21 pediatric implantations	No procedural complications; entry/target errors differed	Pediatric platform comparison
Lee et al. [13]	LITT	Robot-assisted MRI-guided	Pediatric epilepsy	Evaluated accuracy of robot-assisted MRI-guided laser-fiber placement in children with epilepsy	Pediatric LITT evidence

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ACCURACY AND SAFETY OUTCOMES

Robotic-assisted stereotactic systems have rapidly gained traction in neurosurgery, moving from retrospective case series to higher-level evidence (meta-analyses and randomized trials) that highlight advantages in DBS and sEEG. Philipp et al. [43] analyzed 6,056 trajectories and reported lower target error with robot-assisted stereotaxy compared with manual approaches. In their meta-regression, reported accuracy improved over publication years, and frameless technique and intraoperative electrophysiology were each associated with higher target error within the model. In DBS, robotic accuracy improved by 0.057 mm annually, while frameless registration (1.77 vs. 2.69 mm) and intraoperative electrophysiologic testing (+0.45 mm) contributed to higher placement error. In another review, Fayed et al. [44] compared various robotic platforms and registration methods in DBS, noting significantly better accuracy with floor-mounted systems (0.90 ± 0.46 mm vs. 1.12 ± 0.54 mm) and bone fiducial–based registration (0.88 ± 0.46 mm vs. 1.14 ± 0.52 mm). More recently, Dashtkoohi et al. reported pooled mean accuracy for robot-assisted DBS of 1.04 mm radial error (95% CI 0.93–1.15) and 1.19 mm 3D Euclidean error (95% CI 0.94–1.45), with accuracy and complication rates comparable to conventional stereotactic DBS [45]

With regards to sEEG, Vasconcellos et al. [28] analyzed 29 studies (855 patients, 8,184 electrodes) across four robotic platforms (ROSA, Neuromate, Sinovation, iSYS1). They observed mean entry and target errors of 1.48 mm and 2.13 mm, respectively comparable or superior to frame-based methods. ROSA showed the highest target error (2.5 mm) among surveyed systems, and iSYS1 the lowest (1.61 mm). Regarding complication rates, Cardinale et al. [10] noted fewer major complications with robotics in nearly 500 sEEG cases (1.2% vs. 2.6%), while González-Martínez et al. [46] reported comparable complication rates (4% vs. 3%). Similarly, Kaewborisutsakul et al. [47] detected no significant differences in adverse events or hemorrhage rates in 416 ROSA-assisted sEEG procedures compared with traditional approaches. Vasconcellos et al. [28] reported an overall complication rate of 7.69% among 855 robot-assisted sEEG cases, with most events being minor or self-limiting. Pediatric sEEG series generally support feasibility and acceptable accuracy, but complication rates should be interpreted cautiously because hemorrhage risk, skull thickness, fixation strategy, and electrode stability may differ from adult cohorts [11,40,48–50]. In DBS, Huang et al. [51] documented a 12% complication rate in 732 Parkinson's patients, aligning with the 0–28% reported for frame-based DBS, implying no additional risk from robotics.

OPERATIVE TIME

In most comparative studies, robotic workflows provide a variable but generally significant reduction in operative time compared with manual methods. Although early adoption sometimes resulted in comparable or slightly longer operative times (likely because of the learning curve or extra imaging steps) [52,53], the majority of investigations [54–59] consistently report net time savings. The most striking difference was described by González-Martínez et al. who reported a 3.5-hour time savings in 101 robotic versus historical frame-based cases [46].

Some studies also analyzed the duration of specific phases of the stereotactic workflow: for example, two studies focusing on per-electrode metrics [54,55] found 2.5–3.5 minutes saved per electrode with robotic systems, whereas another study [15] reported a 14-minute reduction in the frame-based registration phase compared to the frameless. A recent meta-analysis by Gomes et al. demonstrated a −23.66-minute mean difference favoring robot-assisted over manually guided SEEG, reinforcing the overall trend toward shorter operative times [55]. Device-level subgroup times varied widely (e.g., Neuromate 36.6 vs Sinovation 9.9 minutes/electrode), likely reflecting heterogeneity in workflow definitions, case complexity, and institutional learning curves; these values should not be interpreted as intrinsic device performance. Learning curve data also remain limited but indicate that proficiency develops over an initial learning phase. In a CUSUM analysis, learning phases were approximately 20 DBS cases and 16 sEEG cases, varying by team and workflow, highlighting the importance of structured training and standardized OR roles [60]

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DISCUSSION

Few surgical fields demand the precision required in functional neurosurgery. While minor targeting deviations can still yield therapeutic benefit, an optimal “sweet spot” exists where efficacy is maximized and adverse effects minimized. Available evidence suggests that DBS leads placed within approximately 2 mm of the intended target often do not require repositioning to improve motor outcomes, although a universal accuracy cutoff has not been established. Even so, deviations as small as ~1 mm may meaningfully shift the volume of tissue activated, underscoring the importance of precise targeting [61–66].

Beyond patient confidence in robotic guidance [67], robotics must outperform manual methods in key metrics (e.g., accuracy, speed, safety, or cost) to gain broad acceptance. Designing robots for linear electrode insertions is simpler than creating systems capable of skin incision or brain retraction, which would require advanced video-recognition AI. However, linear trajectories are not the only substantial advantage of stereotactic robots over general-purpose surgical systems (which are designed for broader tasks like incision, retraction, or bone removal). Stereotactic platforms also benefit from the rigid cranial structure. The skull’s inflexibility, coupled with the delicate nature of brain tissue, imposes stringent design constraints that general-purpose robots often struggle to meet. Unlike in abdominal surgery (where insufflation provides additional working space) the fixed cranial volume precludes such approaches [68]. Yet this rigidity offers a vital benefit during functional procedures: it enables precise patient head localization and stable fixation, ensuring that the robot’s coordinate system remains accurately aligned with the patient’s anatomy throughout the operation.

While conclusive evidence for improved clinical outcomes remains under investigation, multiple studies indicate that robotic accuracy in DBS and sEEG is at least comparable to manual approaches [43,44]. Although some retrospective comparisons are mixed, they generally demonstrate at least non-inferior performance [9,10,25]. However, these estimates may be conservative, as they often compare well-established manual workflows with relatively new robotic ones still subject to a learning curve.

These findings should be interpreted cautiously in pediatric neurosurgery. Most pediatric evidence remains retrospective, single-center, and concentrated in epilepsy-related procedures, whereas DBS and LITT data are more limited and often indication-specific. Adult and mixed-age accuracy data cannot be directly extrapolated to children because skull thickness, skull size, cranial fixation, fiducial placement, prior cranial surgery, age-dependent anatomy, anesthesia workflow, and radiation exposure may influence registration and operative planning. For pediatric sEEG, trajectory planning must also account for vessel avoidance, electrode stability, and the need to minimize invasiveness. For pediatric DBS, clinical benefit depends not only on stereotactic accuracy but also on dystonia etiology, target selection, disease duration, programming, and neurodevelopmental status. Therefore, robot-assisted stereotaxy should be considered a valuable adjunct in selected pediatric cases rather than a universally superior approach.

By automating critical steps, robotic systems can help avert fatigue-induced inaccuracies and errors that often arise during lengthy, manually executed stereotactic procedures [8,10]. Automation not only mitigates human error but also often shortens operating times [9,40]. One study reported a 3.5-hour reduction in sEEG duration with robotics [40], and decreased surgical time can be translated into lower hospital costs and lower rates of infections [60,61]. Although specific data on stereotactic procedures are limited, experience in spine surgery has shown significant cost savings and reduced complications with robotic assistance [62].

However, many errors found in manual workflows, such as pneumocephalus-induced brain shift [7, 72,73], lead deviation, and registration errors [19,34], can still occur in robotic settings. Widespread adoption also faces obstacles like cost. Some systems come with substantial upfront and maintenance expenses, typically necessitating high patient volumes to justify and offset these costs.

Training is another hurdle: learning curves for robotic DBS and sEEG can exceed 20 cases per procedure type, with true mastery taking even longer [60,74]. Physical constraints in smaller ORs and limited system maneuverability add further logistical challenges.

Yet robotic systems may expand selected functional neurosurgical workflows as platforms become more compact and easier to integrate. Newer platforms feature reduced footprints and improved workflows (e.g., Stealth Autoguide, Brainlab Cirq, Micromate). Moreover, the demand for highly accurate linear trajectories—paramount to functional neurosurgery—continues to drive innovation beyond traditional indications. For example, a recent study documented the first two successful cases of percutaneous balloon compression for trigeminal neuralgia performed with robotic assistance using the ROSA system [75], underscoring the technology's expanding clinical utility. Furthermore, robotic systems have the potential to significantly reduce radiation exposure (an often overlooked advantage), particularly in functional neurosurgery, where physicians experience some of the highest occupational radiation doses in medicine [76].

Despite ongoing barriers to widespread adoption, robotic assistance is likely to expand as platforms become more compact and workflows mature. This trend aligns well with the rapid advances in AI, which have the potential not only to automate routine robotic workflow steps but also to generate sophisticated models that refine electrode trajectories based on known predictive factors for lead deviation. Factors such as pneumocephalus, bone thickness, and entry angle have long been recognized for their impact on lead placement [72,73,77,78]. More recently, Wu et al. used elastography to measure in vivo brain stiffness and demonstrated that electrode trajectories intersecting the internal capsule at more oblique angles exhibit greater deviations, emphasizing tissue mechanics as a key determinant in DBS accuracy [79].

Furthermore, the inherently image- and data-intensive nature of stereotactic procedures could soon enable real-time visualization of electrode trajectories by integrating multimodal imaging data with micro- and macroelectrode recordings [80]. Notably, Oxenford et al. presented a real-time software platform that pairs high-resolution atlas data with preoperative and intraoperative electrophysiological recordings [80]. Validated in a cohort of 52 DBS patients, this approach showed strong agreement between imaging- and physiology-based targets while compensating for brain shift. Moving forward, AI systems could incorporate widely used anatomical parcellation tools—such as FreeSurfer—to further automate trajectory creation. Although AI-based solutions, particularly in sEEG planning, have attracted growing interest [9], they remain at an early stage of clinical translation.

CONCLUSION

Robot-assisted stereotaxy has become an increasingly important adjunct in functional neurosurgery, particularly for trajectory-based procedures such as DBS, sEEG, and LITT. Available data suggest accuracy comparable to conventional stereotactic techniques and potential workflow advantages in selected procedures, although outcomes vary by platform, indication, registration method, and study design. High costs, learning curves, and logistical constraints remain barriers to broader adoption, while AI-assisted planning requires further clinical validation. For pediatric neurosurgery, the strongest current evidence supports robot-assisted stereotaxy in epilepsy-related procedures, especially sEEG, whereas DBS and LITT applications remain promising but less extensively studied. Future pediatric-specific studies should clarify accuracy, safety, operative efficiency, cost-effectiveness, and clinical outcomes. Overall, robotic stereotaxy may support safer and more efficient functional neurosurgical workflows when its use is tailored to patient anatomy, clinical indication, registration strategy, and institutional expertise.

DISCLOSURES

Conflict of interest

Dr. Chengyuan Wu is a paid consultant for Renishaw and a shareholder in ZetaSurgical. The remaining authors declare no conflict of interest.

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Artificial intelligence

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-**Guglielmo Iess**: Writing – original draft, Resources, Investigation, Conceptualization, Data Curation
-**Joao Pedro Ponce:** Visualization, Resources, Review & editing, Project administration
-**Kevin Hines:** Investigation, Supervision
-**Chengyuan Wu:** Writing – review & editing, Validation
-**Caio M. Matias:** Project Administration, Supervision, Writing – review & editing; Conceptualization

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