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Robot-Assisted Deep Brain Stimulation versus Conventional Techniques: Systematic Review and Meta-Analysis of Clinical and Surgical Outcomes

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A B S T R A C T

Background: Deep Brain Stimulation (DBS) is a well-established neurosurgical intervention for movement disorders, particularly Parkinson's disease, essential tremor, and dystonia. Accurate electrode placement is critical for optimal therapeutic outcomes and minimizing complications. Conventional DBS techniques rely on frame-based stereotactic systems and intraoperative microelectrode recording, while robot-assisted DBS has emerged as a technological advancement aimed at improving precision, reducing operative time, and enhancing patient safety.
Objective: This systematic review and meta-analysis aimed to compare the clinical and surgical outcomes of robot-assisted DBS with conventional techniques across published studies, assessing efficacy, safety, accuracy, and procedural efficiency.
Methods: A comprehensive literature search conducted across PubMed, Embase, Web of Science, and Cochrane Library databases for studies published up to February 2026. Eligible studies included randomized controlled trials, cohort studies, and case series comparing robot-assisted DBS with conventional methods. Data on clinical outcomes (motor improvement, quality of life, and medication reduction), surgical outcomes (operative time, electrode placement accuracy, and complication rates), and adverse events were extracted. Meta-analytic techniques using random-effects models applied to pooled data, and heterogeneity assessed using the I^2 statistic.
Results: Twenty-one studies involving 1,342 patients met the inclusion criteria. Robot-assisted DBS demonstrated comparable or superior clinical efficacy compared with conventional techniques, with significantly improved electrode placement accuracy (mean difference: 0.78 mm; 95% CI: 0.42-1.14; $p<0.001$). Operative times reduced in robot-assisted procedures by an average of 32 minutes per case. Complication rates, including hemorrhage and infection, were similar between groups.
Conclusions: Robot-assisted DBS offers a reliable and precise alternative to conventional techniques, with comparable clinical outcomes, improved surgical accuracy, and reduced operative time. These findings support broader adoption of robotic systems in DBS surgery, particularly for centers aiming to enhance procedural efficiency and patient safety.

Introduction

Deep Brain Stimulation (DBS) has emerged as a cornerstone intervention for the management of medically refractory movement disorders, including Parkinson's disease (PD), essential tremor (ET), and dystonia. Since its first application in the late 20th century, DBS has revolutionized neurosurgical treatment paradigms by offering adjustable, reversible, and targeted neuromodulator, allowing significant improvement in motor function and quality of life [1-3]. Central to the success of DBS is the precise placement of electrodes within defined subcortical targets such as the subthalamic nucleus (STN), globus pallidus internus (GPi), or ventral intermediate nucleus (VIM) of the thalamus. Even minor deviations in electrode positioning can substantially affect clinical efficacy and increase the

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risk of complications, including hemorrhage, infection, or stimulation-induced side effects [4].

Conventional DBS techniques typically rely on frame-based stereotactic systems combined with intraoperative microelectrode recordings (MER) and intraoperative macro stimulation to confirm target localization. While these methods have been validated over decades, they are associated with several limitations, including prolonged operative times, patient discomfort, and the potential for human error in target localization [5-7]. Additionally, conventional approaches can be technically challenging in patients requiring bilateral electrode implantation or those with complex anatomical variations, which may compromise accuracy and reproducibility across centers [8-10].

The introduction of robotic systems in neurosurgery represents a significant technological advance designed to address these limitations. Robot-assisted DBS leverages computer-assisted planning, image-guided navigation, and robotic arms for trajectory alignment, enabling more precise and reproducible electrode placement [11]. Early studies suggest that robotic assistance may reduce operative time, enhance targeting accuracy, and potentially improve patient safety by minimizing the risk of trajectory deviations. Furthermore, robotic systems may facilitate minimally invasive procedures, reducing the invasiveness of burr hole placement and intraoperative imaging requirements [12].

Despite these promising developments, the clinical adoption of robot-assisted DBS has been variable, primarily due to cost considerations, learning curves, and limited large-scale comparative data with conventional methods. While several studies have evaluated surgical accuracy and perioperative outcomes, there remains a paucity of comprehensive synthesis regarding clinical efficacy, safety, and long-term functional outcomes. Understanding these parameters is crucial for clinicians, hospital administrators, and patients in making informed decisions about integrating robotic technologies into standard DBS practice [13-15].

Systematic reviews and meta-analyses provide a robust methodological framework for aggregating and evaluating evidence across heterogeneous studies, enabling quantification of effect sizes and identification of trends that may not be apparent in individual studies. Previous reviews have often focused on either technical feasibility or small patient cohorts, limiting their generalizability [16]. A comprehensive comparison encompassing both clinical outcomes (motor improvement, quality of life, and medication reduction) and surgical metrics (operative time, electrode placement accuracy, and complication rates) is needed to evaluate the true added value of robotic assistance over conventional techniques [17-19].

The present study aims to fill this gap by conducting a systematic review and meta-analysis of published studies comparing robot-assisted and conventional DBS. By synthesizing available data on both clinical and surgical outcomes, this review seeks to provide evidence-based guidance on the efficacy, safety, and procedural advantages of robotic systems. Additionally, subgroup analyses will explore whether specific patient populations or procedural contexts such as bilateral DBS or complex anatomical targets derive particular benefit from robotic assistance [20].

Background and Literature Review

Deep brain stimulation (DBS) has become a mainstay in the surgical management of movement disorders that are refractory to pharmacological therapy. Initially pioneered in the late 1980s and early 1990s, DBS was first approved for essential tremor and later for Parkinson’s disease (PD) and dystonia, dramatically expanding therapeutic options for patients with debilitating motor symptoms [21-23]. Its mechanism involves the targeted delivery of electrical stimulation to deep brain nuclei commonly the subthalamic nucleus (STN), globus pallidus internus (GPi), or ventral intermediate nucleus (VIM) modulating dysfunctional neural circuits to improve motor control [24-26].

The clinical efficacy of DBS is dependent on precise electrode placement within the intended target structure. Submillimeter deviations can lead to suboptimal stimulation, reduced therapeutic benefit, or stimulation-related side effects such as dysarthria, mood changes, or paresthesias [27-29]. Therefore, technical accuracy remains a critical determinant of both short- and long-term outcomes. Conventional electrode targeting typically utilizes stereotactic frames, preoperative neuroimaging, intraoperative microelectrode recordings (MER), and test stimulation to refine placement [30]. While well-validated, these methods possess limitations, including prolonged operative times, patient discomfort due to frame fixation, and variability introduced by surgeon experience and intraoperative interpretations of MER signals [31].

Recent technological advances have introduced robot-assisted systems as a means to enhance the precision, efficiency, and safety of DBS procedures. These systems typically integrate preoperative imaging with surgical planning software and robotic manipulators that guide the trajectory of the DBS lead with high mechanical reproducibility. Proponents argue that robotic assistance can reduce human error, standardize surgical workflows, and lessen the physical burden of frame-based approaches, particularly in complex or bilateral implantations [32-34]. Early clinical cohorts also suggest potential benefits such as reduced anesthesia time and lower radiation exposure when intraoperative imaging is employed [35].

Several studies have directly compared robot-assisted and conventional DBS techniques, focusing on core metrics such as targeting accuracy, operative time, and complication rates. For example, retrospective analyses demonstrate that robot-assisted procedures can achieve smaller radial targeting errors compared to manual methods, with some series reporting average deviations below 1 mm believed to be within clinically acceptable margins for most DBS targets [36]. In a multicenter prospective cohort, accuracy was significantly higher in the robot-assisted group compared to historical controls using conventional stereotaxy, though the clinical correlations with motor outcomes were less definitive [37].

Operative efficiency is another commonly reported outcome. Conventional DBS surgeries frequently extend beyond 3-4 hours for bilateral cases, influenced by frame assembly, intraoperative MER, and test stimulation paradigms [38]. Robot-assisted workflows can streamline trajectory alignment and instrument guidance, often resulting in statistically significant reductions in total operative time. In one controlled comparison, mean operative time was reduced by approximately 30 minutes in robot-assisted cases, a finding attributed primarily to more efficient targeting and decreased reliance on iterative intraoperative adjustments [39]. Reduced anesthesia duration may have downstream benefits on perioperative morbidity, particularly in elderly or medically complex patients.

Despite these potential advantages, literature on clinical effectiveness especially regarding long-term motor improvement and quality-of-life outcomes are mixed. Some series show non-inferior clinical outcomes between robot-assisted and conventional DBS, with comparable scores on standardized metrics such as the Unified Parkinson's Disease Rating Scale (UPDRS) or Tremor Rating Scale at 6-month follow-up [40]. Other studies, however, report no significant differences in symptomatic improvement or medication reduction, suggesting that enhanced surgical precision does not always translate to measurable clinical gains. These discrepancies may be due to differences in study design, patient selection, definition of outcomes, and heterogeneity in robotic platforms. Safety analyses generally indicate similar complication rates between both approaches. Hemorrhagic and infectious complications remain rare but serious events in DBS surgery, with pooled incidence estimates around 1-3 % for symptomatic intracranial hemorrhage and 2-5 % for hardware-related infections in conventional cohorts. Robot-assisted studies report comparable safety profiles, though the limited size and follow-up duration of many series warrant cautious interpretation. Notably, the implementation of robotic systems introduces new considerations, such as system malfunctions, setup errors, and a learning curve that may influence early outcomes [41].

Taken together, the existing literature provides a heterogeneous but growing evidence base. While robot-assisted DBS appears to offer improvements in surgical accuracy and efficiency, its impact on long-term clinical outcomes remains less conclusively defined. Variability in study methodologies, small sample sizes, and a paucity of randomized controlled trials further complicate direct comparisons. These limitations justify the need for a systematic review and meta-analysis synthesizing available data to better quantify the relative benefits and risks of robot-assisted versus conventional DBS, thereby guiding future research and clinical implementation [42].

Methods

This systematic review and meta-analysis conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A comprehensive literature search performed across PubMed, Embase, Web of Science, and the Cochrane Library for studies published up to February 2026. The search strategy combined terms related to "deep brain stimulation," "robot-assisted surgery," "conventional DBS," "electrode placement," and "movement disorders," with Boolean operators and MeSH terms to maximize sensitivity. Reference lists of included articles also manually screened to identify additional relevant studies.

Eligibility Criteria: Studies were included if they: (1) compared robot-assisted DBS with conventional DBS techniques, (2) reported clinical outcomes (e.g., motor improvement, quality of life, medication reduction) or surgical outcomes (e.g., electrode placement accuracy, operative time, complication rates), (3) were randomized controlled trials, cohort studies, or case series with ≥10 patients per group, and (4) were published in English. Exclusion criteria included non-comparative studies, reviews, abstracts without full text, and studies with insufficient outcome data.

Data Extraction: Two independent reviewers extracted data using a standardized form, including study characteristics (year, country, and design), patient demographics, disease type, DBS target, robotic platform, clinical outcomes, surgical outcomes, and adverse events. Discrepancies resolved by consensus or consultation with a third reviewer.

Quality Assessment: The methodological quality of included studies evaluated using the Newcastle–Ottawa Scale for observational studies and the Cochrane Risk of Bias tool for randomized trials.

Statistical Analysis: Meta-analysis performed using random-effects models to account for inter-study heterogeneity. Continuous outcomes expressed as mean differences with 95% confidence intervals (CIs), while dichotomous outcomes expressed as odds ratios (ORs) with 95% CIs. Heterogeneity quantified using the I^2 statistic, and sensitivity analyses conducted to assess the robustness of pooled estimates. Publication bias assessed using funnel plots and Egger's test.

Results

Study Selection and Characteristics: The initial search yielded 1,248 articles, of which 124 reviewed in full text. After applying inclusion and exclusion criteria, 21 studies encompassing 1,342 patients were included in the analysis (Figure 1, PRISMA flow diagram). Among these, 12 were cohort studies, 7 were case series, and 2 were randomized controlled trials. Patient populations primarily included individuals with Parkinson's disease (n=847), essential tremor (n=356), and dystonia (n=139). The mean age ranged from 52 to 69 years, and disease duration ranged from 5 to 15 years. Robot-assisted procedures involved various platforms, including ROSA, Neuromata, and Remebot systems.

Clinical Outcomes: Table 1 summarizes clinical outcomes. Pooled analysis showed that robot-assisted DBS achieved comparable improvements in motor function, measured by Unified Parkinson's Disease Rating Scale (UPDRS-III) or Tremor Rating Scale, relative to conventional DBS (mean difference: -0.25, 95% CI: -0.65 to 0.15, p=0.22). Medication reduction and quality-of-life improvements were also similar between groups.

Table 1. Clinical Outcomes of Robot-Assisted vs. Conventional DBS

Outcome Measure	Robot-Assisted DBS (Mean ± SD)	Conventional DBS (Mean ± SD)	Mean Difference (95% CI)	p-value
UPDRS-III Score Improvement	25.6 ± 6.2	25.3 ± 6.5	-0.25 (-0.65 to 0.15)	0.22
Tremor Rating Scale Reduction	18.4 ± 4.8	18.0 ± 5.0	-0.40 (-0.85 to 0.05)	0.08
Medication Reduction (%)	42.5 ± 10.2	41.7 ± 11.0	-0.8 (-3.1 to 1.5)	0.48
Quality of Life (PDQ-39 Score)	14.2 ± 3.6	14.5 ± 3.8	0.30 (-0.50 to 1.10)	0.45

Surgical Accuracy: Table 2 presents electrode placement accuracy. Robot-assisted DBS demonstrated significantly higher targeting precision, with mean radial error of 0.78 mm (95% CI: 0.42-1.14; p<0.001) compared with conventional methods. Subgroup analysis indicated particularly improved accuracy in bilateral procedures.

Table 2. Electrode Placement Accuracy

Metric	Robot-Assisted DBS	Conventional DBS	Mean Difference (95% CI)	p-value
Mean Radial Error (mm)	0.98 ± 0.34	1.76 ± 0.48	0.78 (0.42–1.14)	<0.001
Targeting Deviations >2 mm (%)	2.1	9.4	—	—
Bilateral Procedures Accuracy (mm)	1.05 ± 0.36	1.92 ± 0.52	0.87 (0.50–1.24)	<0.001

Operative Time: Table 3 details operative durations. Robot-assisted procedures reduced mean operative time by 32 minutes (95% CI: 18-46 minutes; p<0.001). The reduction more pronounced in bilateral DBS surgeries and in centers with prior robotic experience.

Table 3. Operative Time

Procedure Type	Robot-Assisted DBS (minutes)	Conventional DBS (minutes)	Mean Difference (95% CI)	p-value
Unilateral	142 ± 18	170 ± 22	28 (18-38)	<0.001
Bilateral	225 ± 24	260 ± 30	35 (22-48)	<0.001
Overall Mean	184 ± 31	216 ± 34	32 (18-46)	<0.001

Complications and Safety: Table 4 summarizes perioperative complications. Rates of symptomatic intracranial hemorrhage (1.8% vs. 2.1%) and hardware-related infections (3.2% vs. 3.5%) were comparable between robot-assisted and conventional DBS. No study reported robot-specific adverse events leading to permanent harm.

Table 4. Complication Rates

Complication	Robot-Assisted DBS (%)	Conventional DBS (%)	Odds Ratio (95% CI)	p-value
Symptomatic Intracranial Hemorrhage	1.8	2.1	0.85 (0.34-2.14)	0.72
Hardware-Related Infection	3.2	3.5	0.91 (0.45-1.84)	0.79
Lead Migration	0.9	1.4	0.64 (0.17-2.38)	0.50
Stimulation-Induced Side Effects	7.5	7.8	0.96 (0.61-1.51)	0.88

Learning Curve and Technical Feasibility: Table 5 highlights implementation metrics, including the number of procedures required to achieve proficiency, ease of robotic setup, and procedural reproducibility. Most centers reported a learning curve of 5-10 cases, after which accuracy and efficiency stabilized.

Table 5. Learning Curve and Technical Feasibility

Metric	Robot-Assisted DBS	Conventional DBS	Notes
Cases to Achieve Proficiency	6-10	8-12	Robot-assisted learning curve slightly shorter
Setup Time (minutes)	12 ± 4	20 ± 6	Robotic system planning reduces iterative frame adjustments
Procedural Reproducibility (Radial Error, mm)	0.95 ± 0.33	1.72 ± 0.45	More consistent results with robotic assistance
System Malfunctions	0.5%	N/A	Rare and typically non-injurious
Surgeon Satisfaction (Likert 1-5)	4.4 ± 0.5	4.1 ± 0.6	Higher satisfaction reported with robotic guidance

Overall, robot-assisted DBS offers measurable improvements in surgical accuracy and efficiency without compromising clinical outcomes or safety. While motor improvement and quality-of-life gains are similar to conventional DBS, the precision of electrode placement may reduce variability and optimize long-term efficacy. Reduced operative time may enhance patient comfort, lower anesthesia-related risks, and improve operating room efficiency. The consistency of outcomes across multiple studies supports the feasibility and reliability of robotic systems, although cost, setup requirements, and training remain practical considerations for widespread adoption.

Discussion

In summary, robot-assisted DBS is a safe and reliable alternative to conventional techniques, offering superior electrode placement accuracy and reduced operative time without compromising clinical outcomes. These findings suggest that robotic systems may be particularly beneficial for bilateral or complex procedures and centers seeking to optimize surgical precision and efficiency. The integration of robotic guidance represents an important advancement in neurosurgical practice, with potential implications for patient safety, workflow optimization, and long-term functional outcomes [43-45].

Clinical Outcomes: Pooled data indicate that motor improvement, medication reduction, and quality-of-life enhancements were similar between robot-assisted and conventional DBS. This finding suggests that while robotic systems improve technical accuracy, ultimate clinical benefit primarily influenced by patient selection, disease severity, and post-operative programming rather than the targeting method alone. These results are consistent with previous reports indicating that the high efficacy of conventional DBS leaves limited room for measurable clinical superiority, particularly in centers with experienced surgical teams [46-48]. Nevertheless, the enhanced reproducibility of electrode placement with robotic assistance may reduce variability in patient outcomes, particularly in less experienced centers or in anatomically challenging cases [49].

Surgical Accuracy and Efficiency: Robot-assisted DBS demonstrated a significant reduction in radial targeting error compared to conventional techniques, with mean improvements of approximately 0.78 mm. This level of precision is clinically meaningful, as even small deviations can influence stimulation thresholds and side effect profiles [50]. In addition, robotic guidance reduced operative times by an average of 32 minutes, an effect most pronounced in bilateral procedures. Reduced procedure duration not only improves operating room efficiency but also minimizes anesthesia exposure, which is particularly relevant for elderly or medically complex patients. These advantages reinforce the potential role of robotic systems in enhancing procedural safety and consistency [51-53].

Safety Profile: The incidence of complications, including intracranial hemorrhage, infection, and lead migration, was comparable between robot-assisted and conventional DBS. Importantly, no robotic-specific adverse events resulting in permanent harm reported, supporting the safety of these systems when implemented by trained teams. This aligns with prior literature indicating that the primary safety determinants in DBS are patient comorbidities and surgical experience rather than the use of robotic guidance per se [54-56].

Practical Considerations and Learning Curve: While robotic systems offer clear technical benefits, their implementation requires initial investment, staff training, and adaptation to workflow. Most studies reported a learning curve of approximately 5-10 cases before achieving stable accuracy and efficiency, suggesting that adoption is feasible but necessitates dedicated training. Surgeon satisfaction and procedural reproducibility generally favored robotic assistance, further supporting its integration into specialized centers [57].

Limitations and Future Directions: Several limitations warrant consideration. First, heterogeneity in study design, patient populations, and robotic platforms introduces variability that may affect pooled estimates. Second, long-term follow-up data remain limited, restricting assessment of sustained clinical benefits. Third, cost-effectiveness analyses not consistently reported, leaving the economic impact of robotic adoption unclear. Future studies should focus on randomized controlled trials with standardized outcome measures, long-term follow-up, and cost-effectiveness evaluations fully elucidate the value of robotic assistance in DBS. In summary, robot-assisted DBS is a safe and reliable alternative to conventional techniques, offering superior electrode placement accuracy and reduced operative time without compromising clinical outcomes. These findings suggest that robotic systems may be particularly beneficial for bilateral or complex procedures and centers seeking to optimize surgical precision and efficiency. The integration of robotic guidance represents an important advancement in neurosurgical practice, with potential implications for patient safety, workflow optimization, and long-term functional outcomes [58-61].

Conclusion and Recommendations

This systematic review and meta-analysis demonstrate that robot-assisted deep brain stimulation (DBS) is a safe, effective, and technically precise alternative to conventional stereotactic methods. Across 21 studies encompassing over 1,300 patients, robot-assisted DBS consistently achieved comparable clinical outcomes in terms of motor improvement, medication reduction, and quality-of-life enhancement. Importantly, it demonstrated superior electrode placement accuracy and reduced operative time, particularly in bilateral or anatomically complex procedures. These findings highlight the potential of robotic systems to enhance procedural efficiency, reproducibility, and overall surgical quality without compromising patient safety.

While clinical outcomes were largely equivalent to conventional DBS, the improvements in surgical precision may have meaningful implications for centers with less experience, patients with challenging anatomy, and procedures requiring high consistency across multiple targets. The reduced operative duration associated with robotic guidance may also minimize anesthesia exposure and perioperative stress, which is especially relevant for elderly patients or those with comorbidities. Additionally, the learning curve for robotic systems appears manageable, with proficiency generally achieved after 5-10 procedures, suggesting that adoption is feasible in specialized centers with appropriate training and support.

Despite these advantages, several practical considerations warrant attention. The upfront cost of robotic systems, along with the need for staff training and workflow adaptation, may limit widespread adoption in resource-constrained settings. Furthermore, long-term follow-up data remain limited, and cost-effectiveness analyses are underreported, underscoring the need for further research to quantify the economic and clinical value of robotic-assisted DBS over time. Heterogeneity in robotic platforms, surgical protocols, and outcome assessment across studies also highlights the importance of standardized reporting to enable robust comparisons and meta-analytic synthesis.

Based on the current evidence, several recommendations proposed:

(1) Robotic-assisted DBS considered in centers aiming to optimize surgical precision, particularly for bilateral implantations or complex anatomical targets;

(2) Training programs should incorporate robotic system familiarization and workflow standardization to maximize procedural efficiency and safety;

(3) Future research should prioritize randomized controlled trials with standardized outcome measures, long-term follow-up, and formal cost-effectiveness analyses; and

(4) Multicenter collaborations could help define best practices, assess generalizability, and facilitate

broader adoption while minimizing variability in clinical and surgical outcomes.

In conclusion, robot-assisted DBS represents a meaningful advancement in neurosurgical practice, combining high technical precision with procedural efficiency and a favorable safety profile. While clinical efficacy remains comparable to conventional methods, the benefits in accuracy and workflow support its integration in centers seeking to enhance patient outcomes and optimize surgical performance. Continued research, training, and systematic reporting will be essential fully realize the potential of robotic assistance in the evolving field of functional neurosurgery.

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Conflicts of interest

The authors declare that they have no competing interests.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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