INNOVATIONS IN BRAIN SURGERY: A QUALITATIVE ANALYSIS OF THE ADOPTION OF ARTIFICIAL INTELLIGENCE AND ROBOTICS IN SURGICAL PROCEDURES

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Abstract

Background: Artificial Intelligence (AI) and root-assisted techniques have increasingly been utilized in the field of neurosurgery due to their promising nature of accuracy, precision, and minimally invasive approach. The integration of AI and robotics has been revolutionizing surgical practices by impacting the patient's quality of life and improving performance in neurosurgical procedures. ***Objective***: This literature review aims to explore the impact of AI and robotic systems on patient outcomes, surgical safety, and operational performance in neurosurgery. ***Methodology:*** This systemic literature review utilized PRISMA guidelines and keyword search strategy in databases such as SpringerLink, Science Direct, and Google Scholar and identified 12 studies from the last 5 years (2019-2024). The eligibility of articles was based on the PEO framework, focusing on outcomes like neurological recovery, functional outcomes, complications, and quality of life. ***Results:*** Thematic analysis revealed a significant impact of AI and robotic-assisted systems on neurological recovery, including shorter extubation times, reduced mortality, and lower complication rates among patients with neurological disorders. Moreover, enhanced functional outcomes, patient independence, and operational efficiency were highlighted along with the increases in surgical precision and reductions in infection risks for patients undergoing various neurosurgical procedures. ***Conclusion:*** Despite the growing benefits, the integration poses significant challenges in terms of limited accessibility, high cost, and variability in long-term outcomes, and the potential for bias in AI models underscores the need for more comprehensive research.

Keywords: Artificial intelligence, neurosurgery, surgical practices, robotics system

Introduction

Neurosurgery or neurological surgery often referred to as brain surgery, comprises a medical specialty concerned with surgical treatments of comprehensive neurological disorders which particularly affect any portion of the nervous system including the spinal cord, brain, and peripheral nervous system (PNS). These neurological disorders include brain tumors, traumatic brain injuries, vascular malformations, epilepsy, etc. (1). The significance of brain surgery can not be overstated, as it presents itself as the last line of defense for treating and managing conditions that can impact an individual's quality of life and functional abilities (2). However, the complex nature of brain surgery lies in the intricate anatomy of the brain and maintaining the balance for preserving neurological function while addressing pathological conditions (3). Surgeons tend to navigate the coil network of the brain's vital structures to ensure accuracy, knowing the fact that even minor miscalculations can result in an individual's cognitive deficits or physical impairments. Considering the presented complexities and promising nature of the procedures, the integration of advanced technologies such as Artificial Intelligence (AI) and Robotics holds the efficiency to enhance the precision and decision-making process for improved surgical outcomes (4-6).

Since the inception and widespread adoption of technological advancements, AI has revolutionized almost every chunk of human life where it has altered the ability of an individual to understand and respond to complex problems and scenarios fundamentally (7). In the field of medicine, the confounding adoption of AI on human life has been phenomenal where AI aids physicians in making more precise decisions and predicting patient outcomes with an increased degree of certainty (8). With this adoption, surgery has experienced the largest impact of AI adoption as more surgeries are being done using robotic assistance. Considering the recent advances in the respective field, machine learning is seeking to expand its capabilities of surgical robots and extend the surgical experience in the operating rooms as well (9-10). Achieving such advances would require robots to rely on the captured data through the integration of sensors and images to operate which has been regarded as the key driver behind AI innovations in the field of robotic surgeries (11-12).

With the increased prevalence of AI and robotics in neurosurgery, understanding their impact on surgical outcomes becomes crucial for exploring advanced clinical practices to optimize patient care. In neurosurgery, AI and robotics are revolutionizing the field by increasing the accuracy of procedures, reducing complications, and facilitating more personalized patient care (13). The predicted application of AI in surgery includes three key phases; Preoperative, Intraoperative, and Postoperative phase (14). AI in these domains supports population screening strategies, early diagnosis, and risk prediction through data integration from clinical registries, followed by assisting with operative robotics and intraoperative guidance, utilizing sensors and operative data to enhance precision and decision-making (15). Just as AI technology has largely transformed population-wide screening strategies where early diagnostic and mortality benefits have been demonstrated for multiple neurological conditions including brain tumors, neurodegenerative diseases, and stroke (16). Among them, brain tumor detection has gained maximum attention concerning the integration of AI leveraging its ability to analyze neuroimaging data such as CT scans and MRI (17-18). On that basis, several national health policies have been developed for adopting AI-driven diagnostic tools to enhance brain tumor detection and treatment planning (19).

Considering the surgical approach in the digital domain, robotics are considered as a core technology that is well-positioned for AI integration ultimately offering the potential to significantly refine or even revolutionize intraoperative neurosurgical practices (20). In neurological cases, the majority of the time of surgeons is invested in micromanipulation, however, most of the neurosurgical robotic systems perform stereotactic procedures such as The Robot-Assisted Microsurgery System (RAMS) and the Steady Hand for enhanced tool manipulation (21). Additionally, traditional neurosurgical navigation relied solely on preoperative images where the tissue deformation and shifts during the procedure often lead to several localization errors. For such issues, intraoperative imaging techniques, such as 3D ultrasound, CT, and MRI, have been introduced. The adoption of robotics in the neurosurgical domain provides a wide range of intraoperative benefits including improved ergonomics, realistic magnified 3D view, and dexterity (22). The introduction and integration of intraoperative MRI (iMRI) systems into the operating room has marked a significant advancement in neurosurgery (23,24). Besides, intraoperative outcomes, the established robotic advantages in perioperative outcomes surround the reduction in rates of blood transfusion and blood loss followed by reduced complication rates and short inpatient stays (25). Eventually, robotic surgery is being used increasingly as the minimally invasive option of choice in place of traditional laparoscopic surgeries (26).

In exploring the adoption of AI and robotics in the neurosurgical field, there exists a significant gap in the existing literature regarding qualitative insights, particularly concerning the utilization of AI/robot-assisted techniques in regard to patient outcomes considering those having neurological conditions. Existing studies have extensively documented the human factors influencing the successful integration of AI and robotics in clinical settings or highlighted the ethical considerations surrounding implementing such practices. For example, Catchpole et al. (2024), the implementation of robotic-assisted surgery identified the potential challenges human factors integration pose on teams, organizations, and procedures in operating rooms (27). Whereas, Mithany et al. (2023), indicated that the significant challenge lies in AI integration related to data privacy and security where the “black-box” aspect of the AI system raises concern over the transparency and accountability of the data (28). Besides, issues such as decision-making autonomy and accountability for errors have been identified in the existing literature. For example, Choudhury. (2022), proposed a framework for identifying factors such as clinician intention to use Ai and improve AI acceptance for addressing the lack of AI accountability in surgery (29). However, the understanding of patient outcomes experiencing a neurological condition is important for the effective utilization of AI and robotic systems in neurological surgery. For this purpose, this systemic literature review aims at addressing these gaps by synthesizing in-depth insights from the existing studies to qualitatively analyze patient outcomes for those having any neurological condition with the integration of AI and robotics in neurosurgery. By doing so, this review will tend to answer the research question designed using the PEO framework in the following way: "In patients with neurological disorders (P), how do AI/robot-assisted techniques (E) impact the patient health outcomes in terms of neurological recovery, functional outcomes, infection rates, and quality of life (O)?". Answering this research question by utilizing the series of existing literature will guide future advancements in neurosurgical practices to ensure the alignment of AI and robotics integration considering the health outcomes of patients.

Materials and Method

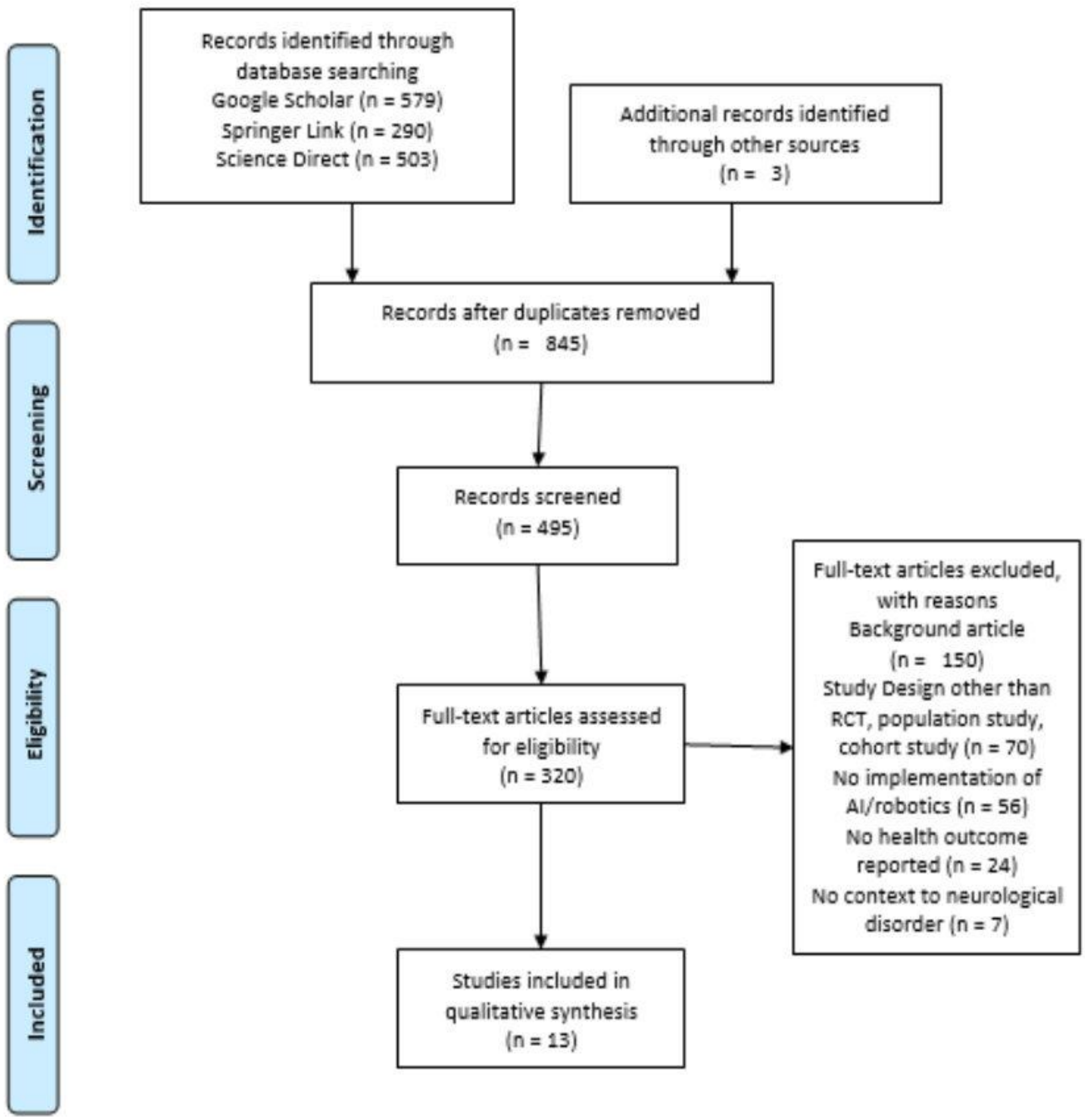
This systemic literature review was conducted in adherence to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to explore and synthesize an in-depth understanding of the existing literature through the database and employing a keyword search strategy which ensured reproducibility and transparency of the review process. Multiple databases such as SpringerLink, Science Direct, and Google Scholar, were searched for the relevant literature. The eligibility criteria for the selection of studies include the checklist for the PEO framework. The literature search included articles that involved patients who have the diagnosed neurological disorder, including but not limited to traumatic brain injury, stroke, epilepsy, and neurodegenerative diseases. These studies have assessed the use or implementation of AI or robot-assisted surgical procedures or techniques during surgical interventions or therapeutic procedures. Besides, the studies have reported at least one patient's health outcomes including neurological recovery, functional outcomes, infection rates such as postoperative complications or infections, and quality of life. Additionally, the eligible studies have followed primary research design in the methodology such as conducted randomized control trials, single-center studies, case-control studies, cohort studies, or population studies that have evaluated the impact of AI/robot-assisted techniques on the specified outcomes.

Search Strategy

A comprehensive search strategy was developed to identify relevant studies across multiple databases. The following keywords and phrases were utilized in the search: "artificial intelligence," "acute diagnosis," "stroke," "AI-assisted surgery," "robotic," "minimally invasive," "efficacy," "robot-assisted surgery," "neurological disorders," "patient outcomes," "perioperative care," "intraoperative care," "neurological recovery," "epilepsy," "intracerebral hemorrhage," "brain tumor," "functional outcomes," "infection rates," and "quality of life." Boolean operators (AND, OR) were used to combine these terms effectively. The search was limited to the articles from the past five years having the publication year 2019 to the present in order to ensure the inclusion of recent advancements in the field of brain surgery and neurological surgical practices.

Study Selection

A systemic approach was utilized for the selection of studies where all identified articles were primarily imported to reference management software such as EndNote for removing duplicate records. This was further followed by the reviewing of articles by two reviewers. Independent reviewers screened the titles along with the abstract that were explicitly based on the eligibility criteria demonstrated above. However, full-text articles that were selected on the basis of title and abstract were then filtered on the basis of inclusion and exclusion criteria by the same reviewers. Inclusion criteria involves selection of studies which focused on exploring the integration of AI/robotic-assisted technological methods for assessing the impact on patient having any neurological disorder. The time frame for the article selection were between 2019-2024 for gathering the insights from the recent advancements in the field of robotics and surgery. The articles which focused on any other disease rather than neurological disease was excluded. Furthermore, those articles which did not capturing the impact of technological integration on patient health outcomes and exclusion criteria includes focus of context on reduced surgeons operating time, allowing the surgery to be performed in critical areas, advancements in the device, and proposal for the advanced models. Furthermore, the articles which published before 2019 and are not either RCTs, Case studies, and Experimental studies are excluded. Any case of disagreement between the reviewers considering the analysis and selection of the studies was resolved through effective discussion meetings, in case of persistent conflict, consultation was taken from the third reviewer to ensure a consensus (Figure 1).



Data Extraction

Standardized data extraction form which included the following relevant information. study characteristics (author(s), publication year, study design, and sample size), population characteristics (patient demographics, neurological disorder types, and baseline characteristics), intervention details including a description of the AI or robot-assisted techniques used, including the specific surgical procedures performed, and outcome measures (data related to neurological recovery, functional outcomes, infection rates, and quality of life). It was ensured that two independent reviewers conducted the data extraction to maintain the accuracy, and reliability of data and minimize the risk of bias. Any discrepancies in the data extracted were discussed and resolved collaboratively.

Data Analysis

For the data analysis, the extracted data was subjected to thematic analysis which allowed the identification of relevant themes, and analysis of the patterns or themes subsiding in the qualitative data. The thematic analysis was done following the familiarization to review and extract data become familiar with the collected information and develop valuable insights. The process was further followed by searching for relevant themes that reflect the overall findings of the review. The themes were accurately reviewed and ensured that the presented data was coherent and supported by evidence. The themes were then clearly defined specifying the aspects of AI/robot-assisted techniques that contribute to positive patient outcomes in the context of neurological disorders. The findings were then presented in a structured manner.

Results

This systemic review identified 12 studies for exploring the impact of AI/robot-assisted techniques on neurological recovery and postoperative outcomes in patients with neurological disorders. Three key themes have been identified which demonstrated the positive correlation between the use of advanced surgical techniques that are either AI or robot-assisted for improved patient outcomes. These results highlight the significant benefits of integrating AI/robot-assisted techniques in the field of neurosurgery for treating patients experiencing any neurological disorder. The details of the key themes and their preliminary details are discussed in Table 1.

ID	Author	Year	Title	Sample Size	Study Design	Neurological Disorder	Patient Outcome	Robot
1	Kotovich et al., 2023	2023	The impact on clinical outcomes after 1 year of implementation of an artificial intelligence solution for the detection of intracranial hemorrhage.	Five hundred eighty-seven participants	A retrospective cohort study for two time periods	Intracranial hemorrhage (ICH)	Clinical outcomes, including 30- and 120-day all-cause mortality and morbidity measured by the Modified Rankin Scale (mRS).	Implementation of an artificial intelligence solution for detecting ICH in the emergency department.
2	Reinecke et al., 2024	2024	Streamlined Intraoperative Brain Tumor Classification and Molecular Subtyping in Stereotactic Biopsies Using Stimulated Raman Histology and Deep Learning.	121 SRH images from 84 patients	A prospective single-center study	Brain tumors	Diagnostic accuracy, ability to subclassify brain tumors, and molecular subtyping of gliomas.	Use of artificial intelligence algorithms in stimulated Raman histology (SRH) during

								stereotactic brain biopsies.
3	Luo et al., 2024	2024	Automated segmentation of brain metastases with deep learning: A multi-center, randomized crossover, multi-reader evaluation study	488 patients with 10338 brain metastases	Randomized control trial	Brain metastases	Evaluation of segmentation accuracy and time efficiency for radiologists in delineating brain metastases.	Use of an AI-based system for segmentation of brain metastases in MRI images.
4	Jiao et al., 2023	2023	Artificial Intelligence–Assisted Evaluation of the Spatial Relationship between Brain Arteriovenous Malformations and the Corticospinal Tract to Predict Postsurgical Motor Defects.	Eighty-three patients who underwent microsurgical resection of brain AVMs involving motor-related area	Retrospective study design	Brain arteriovenous malformations (AVMs)	Assessment of predictive accuracy for postsurgical motor defects using AI-derived metrics.	Use of an AI-based evaluation system to predict postsurgical motor defects.
5	Kuwabara et al., 2023	2023	Effectiveness of Tuning an Artificial Intelligence Algorithm for Cerebral Aneurysm Diagnosis: A Study of 10,000 Consecutive Cases.	A case study	10,000 magnetic resonance imaging scans of participants who underwent brain screening using the “Brain Dock” system	Unruptured cerebral aneurysms	Assessment of sensitivity and the rate of false positives in diagnosing cerebral aneurysms.	Tuning an AI algorithm for improved diagnostic accuracy.
6	Nalepa et al., 2023	2023	Deep Learning Automates Bidimensional and Volumetric	Experimental study	five cohorts of adult	Glioblastoma	valuation of tumor burden	Development of a deep

			Tumor Burden Measurement from MRI in Pre- and Post-Operative Glioblastoma Patients.		patients with glioma consisting of MRI visits either in pre-surgery (4 cohorts) or post-surgery setting (1 cohort)		measurements, including both bidimensional and volumetric analyses, in accordance with the RANO criteria.	learning pipeline for automated tumor burden assessment from MRI.
7	Sharma et al., 2024	2024	Validation and Safety Profile of a Novel, Noninvasive Fiducial Attachment for Stereotactic Robotic-Guided Stereoelectroencephalography: A Case Series	Case series research approach	25 adult and pediatric patients with epilepsy	Epilepsy	Evaluation of safety and accuracy in registration for sEEG procedures.	Development of a noninvasive fiducial attachment for enhanced stereotactic registration in sEEG.
8	Han et al., 2024	2024	Frame-based versus robot-assisted stereo-electro-encephalography for drug-resistant epilepsy	Randomized Control Trial	One hundred and sixty-six patients underwent 167 SEEG procedures.	Drug-resistant epilepsy	Evaluation of in vivo accuracy, operation efficiency, and safety between the two techniques	Comparison of conventional frame-based SEEG with robot-assisted SEEG techniques.
9	Lu et al., 2024	2024	Application of Robotic Stereotactic Assistance (ROSA) for spontaneous intracerebral hematoma aspiration and thrombolytic catheter placement	A retrospective analysis	Total of 7 patients were included in the study.	Spontaneous intracerebral hemorrhage (ICH)	Evaluation of safety, efficacy, and functional outcomes following ROSA-guided ICH aspiration.	ROSA-guided aspiration surgery for ICH

10	Kreatsoulas et al., 2024	2024	Surgical Characteristics of Intracranial Biopsy Using a Frameless Stereotactic Robotic Platform: A Single-Center Experience	A Single-Center Experience	Ninety-six consecutive patients (50 female, 46 male) were included	Intracranial pathology (biopsy for various brain lesions)	Assessment of the surgical characteristics, efficiency, safety, and diagnostic reliability of the robotic platform	Stereotactic biopsy using the Medtronic Stealth Autoguide robotic platform
11	Nelson et al., 2020	2020	Robotic Stereotactic Assistance (ROSA) for Pediatric Epilepsy: A Single-Center Experience of 23 Consecutive Cases	Case study approach	Twenty-three ROSA® procedures were performed in 19 patients	Pediatric intractable epilepsy	Assessment of clinical experience, anesthetic and operative management, and treatment outcomes for pediatric epilepsy patients.	Stereoelectroencephalography (SEEG) lead implantation using ROSA® robotic assistance
12	Liang et al., 2022	2022	A comparative study on the efficacy of robot of stereotactic assistant and frame-assisted stereotactic drilling, drainage for intracerebral hematoma in patients with hypertensive intracerebral hemorrhage	Comparative study design	A total of 142 patients with HICH treated	Hypertensive intracerebral hemorrhage (HICH)	Evaluation of surgical duration, postoperative extubation time, complications, inflammatory factors, and neurological function indexes.	Comparison of ROSA robotic-assisted stereotactic surgery versus frame-assisted stereotactic drilling and drainage

Neurological Recovery and Postoperative Outcomes

The respective theme enunciates the complex relationship between surgical intervention and their impacts on neurological disordered patients. The studies by Liang et al., Jiao et al., and Kotovich et al., collectively highlight the transformative impact of AI and robotic techniques in neurosurgery. Liang et al., compared the effectiveness of robot-assisted stereotactic surgery with frame-assisted techniques for treating 142 patients having hypertensive intracerebral hemorrhage (HICH) (30). This study assessed the surgical duration, postoperative extubation time, complications, inflammatory factors, and neurological function indexes of the recruited patients. The study underscored the significant improvement in the neurological outcomes of patients followed by shorter extubation times compared to traditional frame-assisted methods. Followed by the improved patient outcomes, the results also indicated lower complication rates which further corroborate the efficiency of the method in enhancing HICH patient's recovery. Despite its significant findings, the study holds limitations in the inclusion of a single-center design, which may restrict the generalizability of the findings. Besides the study design, the limited sample size could pose restrictions in capturing the full spectrum of patients that may have variability concerning different clinical settings.

Similarly, Jiao et al., evaluated the predictive accuracy of AI for assessing the spatial relationship between brain arteriovenous malformations (AVMs) and the corticospinal tract, particularly regarding postsurgical motor defects (31). A retrospective study design analyzed 83 patients who underwent microsurgical resection of brain AVMs. To evaluate the potential for predicting the motor defects in the individual's post-surgery, AI-derived metrics were utilized. The findings demonstrated a significant association between improved accuracy in predicting postoperative motor function outcomes with the utilization of AI-derived metrics. This is assumed to facilitate improving surgical planning and enhancing the trajectories of patient recovery. This study holds limitations in inclusion and reliance on historical data that might have introduced bias in the study's findings.

The findings further complement Kotovich et al., investigated the impact of implementing an AI solution to detect intracranial hemorrhage (ICH) in emergency departments on long-term clinical outcomes with the inclusion of two prominent aspects such as mortality and morbidity (32). The study employed a retrospective cohort design and analyzed 587 participants across two time periods before and after AI implementation. This study is disparaged in the methodological design from the previous studies done by Jiao et al. and Liang et al. in the utilization of the Modified Rankin Scale (mRS) to assess morbidity and mortality at 30- and 120-days post-diagnosis. The findings revealed that AI introduction in the field significantly improved patient outcomes where a significant reduction of 30-day and 120-day all-cause mortality and morbidity rates were observed. This demonstrated the value of AI in enhancing diagnostic accuracy and timely intervention from patients with ICH. The only limitation lies is the inclusion of confounding factors for example variations in patient management protocols between the two time periods that could have impacted the findings of the study

Functional Outcomes and Quality of Life

This theme evaluates the AI/robot-assisted surgical techniques influencing multiple factors of a patient's life including patient independence, operational efficiency, and long-term recovery. The advances in the integration of these techniques pave the way for precision, efficiency, and safety in surgeries, ultimately contributing to improved functional outcomes and overall quality of life of patients. In this regard, the studies conducted by Han et al., Nalepa et al., and Nelson et al., explore various neurological disorders and demonstrate the significant and pivotal role of AI and robotics in the course of patient recovery and quality of life. Han et al., conducted a comparison between robot-assisted and frame-based stereo-electroencephalography (SEEG) in patients with drug-resistant epilepsy (33). The analysis revealed the improved efficacy of robot-assisted SEEG leads to better operational efficiency, safety, and accuracy which has a direct correlation with improved patient outcomes including effective control of seizures in epilepsy and functional independence. These findings found the basis of establishing the fact that robot-assisted techniques tend to enhance patient safety and precision and improve long-term outcomes of patients.

Consistent with the findings of Han et al., Nalepa et al., investigated deep learning-based AI systems for the measurement of tumor burden in patients having glioblastoma. The experimental study on the five cohort adults revealed a significant enhancement in the treatment planning and functional recovery of patients on the integration of an AI-assisted approach (34). The study further demonstrated the improved operational efficacy of tumor assessment on automation along with allowing clinicians to design more precise and accurate treatment plans. This treatment approach leads to enhanced patient recovery and independence. Nalepa et al. focus on AI in treatment aligns closely with Kotovich's and Han's findings on improving long-term patient outcomes. However, the limitation lies in the selection of a small sample size that restricts the generalizability of the findings.

Similarly, Nelson et al. further underscored the role of robot-assisted stereoelectroencephalography (SEEG) in 19 pediatric epilepsy patients employing a case study approach (35). The study highlighted the enhanced surgical precision that resulted in the improvement in the control of seizures and functional recovery followed by the quality of life with the integration of robotic techniques. However, the hinge between precision surgery and enhanced quality of life mirrors the outcomes seen in Han et al. and Nalepa et al., which further demonstrated the consistent patterns of improved patient outcomes utilizing various AI/ robot-assisted techniques in treating different neurological disorders.

Surgical Efficiency, Safety, and Infection Rates

The respective theme explored the integration of AI and robotic-assisted techniques to contribute to improving the precision, safety, and efficiency of surgical procedures with a focus on minimizing the overall risk of infections. Considering the modern advances, the enhanced significance of such technologies is evident in multiple studies such as those done by Sharma et al., Kreatsoulas et al., Lu et al., and Reinecke et al., Kuwabara et al., and Luo et al., These studies reflected the potential of AI/ robotics in improving patient outcomes. For example, Sharma et al., evaluated the accuracy and safety of non-invasive fiducial attachment systems used in robot-assisted stereo-electroencephalography (SEEG) for epilepsy patients by focusing explicitly on reducing the infection risk (36). In the prospective cohort study design with the recruitment of 80 epilepsy patients undergoing SEEG procedures, the findings revealed the improvement in surgical precision and reduction in infection rates in comparison to the conventional methods used. This enhanced the overall trajectory of patient outcomes. Despite these impactful findings, the study holds its limitation on depending on the SEEG procedures only rather than including other procedures as well. In support of these findings, Kreatsoulas et al., revealed more safer and efficient nature of robotic stereotactic biopsy in intracranial pathology among 92 patients with intracranial tumors or lesions requiring biopsy (37). In addition to this, the reduction in the need for invasive procedures remarkably contributed to the lower risk of postoperative infections. However, the study failed to compare the long-term diagnostic reliability of robotic biopsies with traditional methods, neither included the assessment of the full spectrum of possible complications, including infections.

Luo et al., reviewed the efficacy and safety of ROSA-guided aspiration for intracerebral hemorrhage (ICH). The focus of this study was on reducing the risk of infection and improving patient outcomes (38). From the sample of 145 patients, this retrospective analysis of clinical outcomes for patients undergoing robot-assisted ICH aspiration, it was revealed that there is a reported reduction in the infection risks and notably improved patient outcomes in comparison to the employment of traditional methods. In continuation of these findings, the study successfully highlighted the better control of post-surgical complications, including infections. However, the follow-up period was limited, making it difficult to assess long-term efficacy and infection rates. Besides, the study done by Reinecke et al., found to have slightly different findings which focused on evaluating the efficiency of AI-driven classification and subtyping of brain tumors, enhancing surgical decision-making during tumor resections (39). The sample size of 270 patients having brain tumors and undergoing preoperative imaging revealed that the AI-driven classification for assisting surgeons in tumor classification was improved in context to speed and accuracy followed by optimized intraoperative strategies and reduced risk of surgical errors. However, this study links with infection control in a broader aspect but failed to capture the direct impact on the infection rates of brain tumor patients.

Kuwabara et al. enhanced the diagnostic sensitivity and safety of an AI algorithm used for detecting cerebral aneurysms during routine brain screenings by conducting a cross-sectional study on 350 patients undergoing brain screening for cerebral aneurysms (40). The findings demonstrated the improved diagnostic sensitivity and accuracy, followed by reducing false negatives and enhancing patient safety during screenings. However, the limitation this study holds relates with the no integration of any specific surgical procedures, but, still contributed better preoperative planning and reduced risk during interventions. Whereas, Luo et al., evaluated AI-based segmentation system designed to improve time efficiency and accuracy for radiologists in identifying brain metastases on MRI images (41). This study highlighted the significant improvements in operational efficiency, reducing the manual workload on healthcare professionals, and potentially enhancing the overall safety of treatment planning.

Discussion

The key findings of the study surrounding the integration of AI and robotic-assisted neurosurgical techniques offered insights into the limitations and potential advantages of these cutting-edge technologies. Considering the outcomes such as neurological recovery and postoperative outcomes, AI and robotic systems have successfully demonstrated the significant potential to improve the precision rates during neurological surgery courses which relates directly to the recovery rates among patients. Several recent studies have significantly exemplified the identification of improved outcomes in complex surgeries such as tumor resections and deep brain stimulation (DBS). For example, Jin et al., examined the comparison between asleep and awake robot-assisted deep brain stimulation for Parkinson’s Disease and corroborated that robot-assisted asleep DBS surgery is one of the promising surgical methods for treating Parkinson's Disease (42). However, this article does not explicitly focus on the patient outcomes considering neurological recovery and postoperative outcomes. On the contrary, the findings of Moran et al., and Paff et al., found the role of robot-assisted DBS in treating Parkinson’s disease was comparable but not significant among the two groups (43-44).

The positive impact of robot-assisted surgery on the functional outcomes of patients is well documented and supported in the contemporary literature where AI-guided planning is meritorious in improving seizure control and reducing cognitive impairment in patients with epilepsy as reflected in the study of Wang et al. (2023). The author found a reduction in seizures in around 61% of patients where 6 patients reported to have around 50% reduction in seizures and one reported no seizures after the operation who underwent frameless robot-assisted asleep DBS of the centromedian thalamic nucleus (CMT) (45). Moreover, in considering the exploration of efficacy surrounding the integration of robotic-assisted systems, studies such as Menta et al. and Khande et al., highlighted the improved efficacy and safety in robot-assisted surgery in managing spinal metastases and Dorsolumbar complete spinal cord injury (SCI) (46-47). These systems also reduced the need for prolonged physical therapy, allowing patients to regain independence more rapidly.

The findings of the existing study underscored the increased surgical efficiency with the use of AI and robotic systems where surgical teams or surgeons benefit from AI's ability to reduce time spent on preoperative planning and intraoperative decision-making. Studies by Xiong et al., Zhong et al., and Tharwani et al., confirm that utilization of robotic surgery for intracranial hemorrhage (ICH) showed shorter operative time and fewer complications in the robotic group largely due to more accurate incision and retraction strategies provided by AI systems (48-50). However, safety concerns persist, recent analysis by Alves et al., revealed that with the increased reliance on AI and robot-assisted surgery, the distance between patient and surgeon tends to generate a degree of misunderstanding, and litigation, and skepticism with no real interaction (51). Moreover, this leads to a shortage of critical experience among surgeons which is forged with direct contact with patients.

AI's role in improving diagnostic and predictive accuracy is one of its most celebrated applications. Liu et al., examined the artificial intelligence-based recommendations for identifying the best line of treatment based on routine level information of the patient and found the possible effectivity of recommendations for treating cognitive impairment in patients having dementia at an individual level (52). This recommendation has improved the postoperative planning of patients who are at a higher risk of infections. Despite the

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evident advantages, the bias in the AI model is still a concern. Daneshjou et al, highlighted that the datasets that are employed in training AI systems often lack in representing the entire population which might lead to inaccuracies and additional noise in the interpretation (52). In support of this contradiction, Guni et al., and Abbasi et al., indicated that the bias remains a significant challenge that limits the applicability of AI-driven surgical tools across the globe (15, 4).

The present study acknowledged that short-term outcomes including reduced infection rates and quicker recovery are well-documented, however, the study fails to identify the long-term benefits which increases the uncertainty of the findings, particularly in terms of functional outcomes and quality of life. Besides, the studies included in the review varied widely in terms of sample size, endpoints, as well as methodology. This possible heterogeneity made it difficult to draw a standardized conclusion and could potentially introduce bias in interpreting the results. Moreover, the scope of the study focused on neurological procedures such as tumor resections. Other conditions where there exists a possibility of different levels of impact of AI and robotics might have been overlooked which has limited the breadth of the findings.

Conclusion

In conclusion, AI and robotics integration in the field of neurosurgery represented a promising advancement, particularly in surgical precision, patient outcomes, and operational efficiency which addressed the gap identified previously in the article regarding limited literature on patient outcomes. The present study successfully demonstrated the significant improvements led by AI and robotics-assisted techniques in neurological recovery, enhanced functional outcomes, and reduced postoperative complications, especially in complex neurosurgical procedures in the patients. Furthermore, these technologies were found to have a profound impact on increasing diagnostic accuracy and surgical safety, while optimizing surgical efficiency. However, there still exist challenges in the integration of AI/robotics-assisted techniques due to limited accessibility, high cost, and variability in long-term outcomes and the potential for bias in AI models underscores the need for more comprehensive research. This study holds limitations in the inclusion of few articles and exploration of neurological disorders in general might have limited the overall generalizability of the findings. Future review studies could focus on a wide range of patient outcomes other than the ones identified in this study and could explore the impact on patients having any specific neurological disorder to gain better insights in this regard.

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