FUSION OF AI AND ROBOTICS FOR TRANSFORMING NEUROSURGERY

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Abstract - Telesurgery using robotic arms equipped with artificial intelligence represents an innovative direction in the field of neurosurgery, with the potential to improve the precision and efficiency of brain interventions. The purpose of the present study is to analyze the advantages and challenges of this technology, as well as future development directions. The methodology employed involves a systematic analysis of the relevant literature from the last five years. The results suggest that telesurgery using the artificial intelligence and robotic technologies in neurosurgery can facilitate more precise and less invasive interventions; however, there are challenges related to technological integration and clinical acceptance. Additionally, the feasibility of applying telesurgery in neurosurgical interventions is analyzed and discussed. The main conclusion of this study is that telesurgery with robotic arms featuring artificial intelligence has the potential to revolutionize surgical practices but requires further research to overcome current obstacles.

Keywords: Artificial intelligence, Robotics, Neurosurgery, Medical robotics, Telesurgery, Neuroscience, Neurology.

1. Introduction

Artificial Intelligence (AI) encompasses computational systems designed to emulate cognitive functions, particularly focusing on learning, reasoning, and autonomous problem-solving. Modern AI architectures operate through hierarchical learning frameworks, with Machine Learning (ML) and Deep Learning (DL) representing the primary paradigms for medical applications [1].

ML systems utilize statistical and probabilistic methods to extract patterns from structured data, enabling predictive modeling and decision support in clinical settings. Traditional ML approaches rely on feature engineering, where domain experts must explicitly define the relevant attributes for model training. This supervised learning process, while effective for well-defined medical tasks, can be constrained by human bias in feature selection and may not fully capture complex biological patterns.

Deep Learning, a specialized subset of ML (Figure 1), employs artificial neural networks with multiple processing layers to automatically discover representations needed for pattern detection or classification. Unlike traditional ML, DL architectures perform automatic feature extraction, learning increasingly abstract data representations through hierarchical layer structures. This capability has proven particularly valuable in medical imaging analysis, where complex visual patterns must be identified across multiple scales and modalities.

The convergence of enhanced computational capabilities, sophisticated DL architectures, and the availability of large-scale medical datasets has enabled unprecedented advances in clinical applications [2]. These include automated diagnosis support, medical image segmentation, and robotic surgical assistance systems. The self-learning nature of DL systems allows for continuous improvement through exposure to new clinical data, potentially surpassing human-level performance in specific diagnostic and analytical tasks while maintaining consistency and reproducibility.

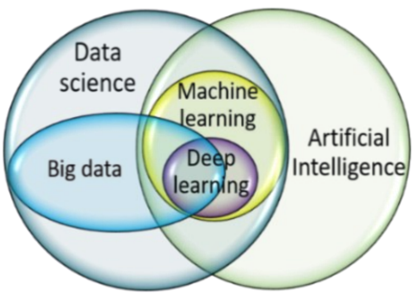

Figure 1: Venn Diagram of Artificial Intelligence

2. Problem Statement

Minimally invasive neurosurgical procedures represent complex interventions demanding exceptional precision and advanced spatial orientation skills. These technically sophisticated operations typically extend beyond traditional surgical timeframes, requiring sustained periods of intense focus and micro-movements. The cognitive and physical demands on surgeons during these extended procedures create a multifaceted challenge: maintaining optimal hand-eye coordination, managing real-time decision-making, and executing precise manipulations within delicate anatomical pathways. The criticality of each movement in neurosurgery, where microscopic precision directly impacts patient outcomes, amplifies the impact of surgeon fatigue. This combination of technical complexity, temporal demands, and human performance factors highlights the value of technological assistance in modern neurosurgery.

These may be factors that boost the approximately 25% of the medical technical errors related to surgical procedures [3] that occur in neurosurgery. In addition to these, the 'human resource crisis' is one of the biggest challenges facing the healthcare sector in recent times [4], especially given that as life expectancy and global population levels increase [5], [6], [7] the demand for healthcare services is intensifying. However, robot-assisted systems have the potential to reduce this burden, providing support at critical moments during an operation. Robots, equipped with AI algorithms, can process data faster and with fewer errors than a human, reducing the risk of bad decisions due to fatigue or stress. Unlike humans, which have a limited lifespan and have to relearn skills with each new generation, AI systems can incorporate accumulated data and knowledge, maintaining consistent performance over the long term. Once an AI system is developed and perfected for surgery, it does not suffer performance degradations due to human factors such as fatigue or emotions. However, there is an undeniable reality related to the unique aspects of human intervention in surgery. Subjective factors, such as the ability to respond empathically and creatively, can have a valuable influence on the success of surgery [8], unfortunately unquantifiable at present. Neurosurgeons utilize their superior lifelong-acquired skills, integrating a combination of technical precision, coordination, adaptability, and operational creativity, while maintaining a strong sense of balance as well as an aesthetic vision throughout the surgical process. These traits, coupled with an ethical and humanitarian mission, are still difficult for AIs to replicate. Also in surgery, information is transmitted to the human brain through the five senses: sight, touch, hearing, taste and smell. This information is processed and transformed into decisions that manifest in actions or words. Of these senses, sight provides about 80% of the information needed. In traditional surgery, sight and touch have always been essential, but in robot-assisted, touch loses its importance, making sight the primary component of surgical decisions [2], [3].

3. AI and Robotics in Surgery

Surgical procedures, which are often performed by visualizing images obtained intraoperatively, are highly compatible with artificial intelligence technologies. This is because digital images can be stored and subsequently used as training data for machine learning algorithms. Computer vision, a core area of AI, has three fundamental steps: classification, to identify the nature of the object in the image, detection, to localize objects in the image, and segmentation, which highlights the parts of the image that belong to the same category. In surgical interventions, segmentation, the last stage of computer vision, is particularly promising as it allows surgeons to operate with extreme precision, relying on automatic interpretation of digital images [9]. The signal captured by cameras and other imaging devices provides a rich source of surgical data and can be obtained in a variety of spectra, depending on the clinical specificity [8]. For example, functional magnetic resonance imaging or fluorescence light imaging can provide additional information about the status of critical brain tissues and structures. These techniques offer a significant advantage in robot-assisted neurosurgery, where precision is central to the success of the operation.

Robotics has brought about a significant revolution in healthcare, transforming the way surgery is performed. One of the main advantages of robotic systems is their ability to offer multiple degrees of freedom, allowing them to perform complex movements [10] and approach surgery with high flexibility. These degrees of freedom are essential for performing delicate maneuvers, allowing surgeons to reach hard-to-reach areas and perform complex techniques.

However, this flexibility also comes with challenges. More complex and varied movements can diminish precision, an imperative in neurosurgery. For this reason, it is necessary to integrate technological process equipment to increase the precision of interventions [11]. These include the AI co-pilot system, which enhances the robot's ability to make informed decisions based on collected data. This intelligent system can analyze data in real time, providing feedback and suggestions to optimize the robot's movements and ensure better accuracy during the intervention.

By combining the flexibility offered by robotics with the increased precision provided by AI, surgeons can benefit from a powerful tool that improves both the safety and outcomes of neurosurgical procedures. This synergy between technology and human expertise marks a new era in modern medicine, promising more efficient and less invasive surgeries that can greatly improve patient experience and surgical success.

Robotic systems used in surgery can be classified into three main categories: active systems, which operate autonomously; semi-active systems, where the surgeon completes the robot's pre-programmed actions; and surgeon-driven systems. Currently, robotic systems applied in surgery are classified as surgeon-driven. These include a mechanical robot placed at the patient's side, connected to a radiation-shielded control station, which allows the operator to control the catheters and guide wires via tactile sensors [12] and joysticks [13]. Implementing robotic systems in endovascular neurosurgery offers several advantages, such as increased stability of the catheter tip, which reduces the need for repeated movements. They also facilitate more efficient navigation through complex vascular anatomy and contribute to decreased radiation exposure for the medical team [14].

The application of AI in surgery (Fig. 2) is being explored in various fields to avoid serious errors during this process by automatically detecting and recognizing critical anatomical structures. Concepts used in surgical procedures are founded on the removal of the affected area along with associated tissues. This approach involves extremely precise dissection of the interface between the area and surrounding tissues, avoiding vital structures such as the blood vessels and nerves [8]. AI can assist in recognizing these structures, providing increased accuracy and minimizing the risk of accidental injury.

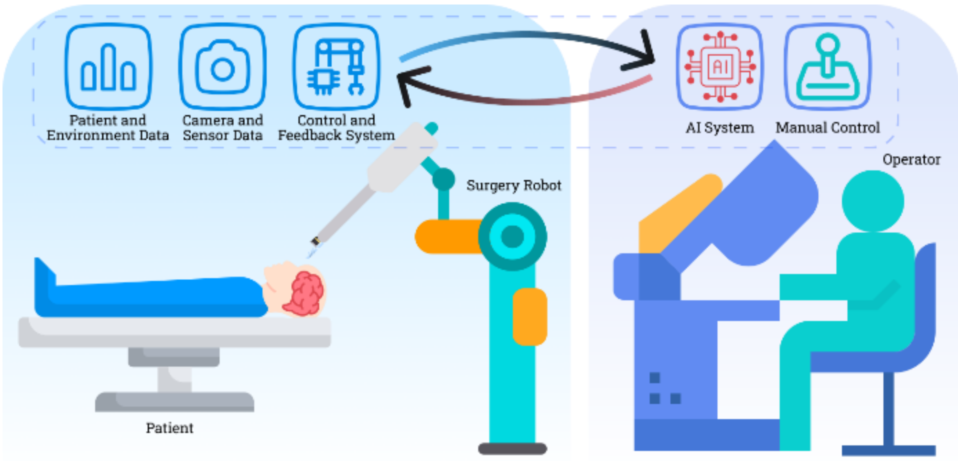

Figure 2: Interaction between Surgical Robot and Operator during telesurgery procedure using AI

Devices used in neurosurgery have evolved significantly due to the implementation of advanced technologies, including robotics and artificial intelligence. These include [15]:

– Neuromate, a commercially available system that includes a floor-mounted robotic arm designed to align and maintain linear trajectory. It facilitates frameless stereotaxis with the ability to perform semi-automated aiming. The Neuromate can also serve as a surgical assistant in endoscopic procedures, with roles such as retraction, illumination, and location correlation with navigation.

– ROSA, commercially available, uses a floor-mounted robotic arm with the same alignment and trajectory maintenance functions, also providing surgical assistance in the endoscopy context.

– Mazor Renaissance, another innovation that is no longer commercially available, features a skull-mounted robotic arm with the role of aligning and maintaining linear trajectory, providing frameless stereotaxis and semi-automated aiming.

– The Stealth Autoguide, manufactured by Medtronic and commercially available, uses a Mayfield clamp to mount the robotic arm, accomplishing the same alignment and trajectory maintenance functions.

– The SurgiScope, a ceiling-mounted surgical microscope from ISIS Robotics, is capable of frameless robotic stereotaxis and can be used for semiautomated targeting, even if that is not its primary purpose.

– CorPath GRX Robotic System, commercially available from Corindus, allows translational and rotational movements of endovascular catheters, facilitating telesurgery. It can perform catheter manipulation on behalf of the primary surgeon, demonstrating an effective collaboration between technology and human expertise.

– NeuroArm, a prototype built and successfully used in the clinic, is not commercially available, but enables open surgical maneuvers scalable in amplitude and speed. This system can perform microsurgical movements on behalf of the surgeon, with the potential to augment fine movements by scaling them and filtering out tremor.

– In the research stage are devices known as Follow the Leader Curved Needles, which guide therapeutic devices to the target through a predetermined but nonlinear path using an MRI (Magnetic Resonance Imaging)-compatible robotic actuator. They provide frameless stereotaxis over complex paths, and the robotic actuator can execute movements on behalf of the surgeon.

– In addition, magnetic navigation systems, currently at the research stage, allow guidance of therapeutic devices by dynamic changes in the magnetic field, providing stereotactic guidance with degrees of freedom not possible by tactile methods and with potential in radiotherapy.

– DaVinci surgical system is widely used in urology, gynecology and general surgery, but is currently limited to cadaveric studies for cranial interventions. This floor-mounted robot translates the movements of the surgeon's hands from a remote console, allowing microsurgical movements to be performed on behalf of the lead surgeon. DaVinci offers scalable motions, tremor filters, articulating instruments and three-dimensional visualization, demonstrating how advanced technology is transforming neurosurgical practice.

Another representative product in the field of AI in telesurgery is Eureka, the first AI-assisted surgical vision system, developed by the company Anaut in 2022 [16]. This system can highlight critical anatomical structures such as connective tissues, nerves and the pancreas in real time, facilitating complex surgeries. Once approved as a medical device, it can be used in combination with robotic and endoscopic surgical systems.

As AI continues to evolve, computer-assisted intervention (CAI) systems are becoming increasingly promising in neurosurgery. One of the main advantages of CAI is its ability to integrate complex data, such as medical imaging, into the planning and execution of interventions. This type of support is characteristic in telesurgery, where the surgeon operates remotely and direct physical interaction with the patient is limited. Another characteristic of CAI is its ability to standardize procedures and eliminate human variability. In neurosurgery [17], where each patient may have a unique anatomy and the surgical challenges are extremely diverse, the use of CAI can ensure greater consistency in the execution of operations. For example, AI algorithms can learn from an extensive database, consisting of thousands or even millions of similar cases, and provide suggestions for the best intervention strategies [9]. This ability to access and learn from historical data gives CAI a considerable advantage over human surgeons, who are limited by personal experience and memory. AI can thus act as a "virtual assistant" that improves decision-making and optimizes clinical outcomes.

AI-based CAI platforms could be a determining factor in addressing current obstacles that limit the efficiency and intelligence of robotic surgery. Robotic feedback systems, together with kinetic data provided by encoders, can help alleviate the constraints associated with vision-based solutions by bringing an additional sensor into the operative process. Thus, AI can become a co-pilot (Fig. 3) that provides novice doctors with skilled assistance, similar to their experienced colleagues [18].

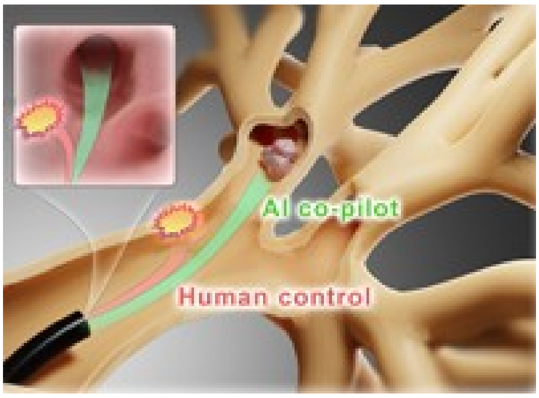

Figure 3: AI Co-Pilot assisting in surgical procedures (Adapted from [18]*)*

However, integrating data from multiple sources remains a complex and open challenge in the field. Cutting-edge approaches using data fusion are particularly focused on automating surgical subtasks, including suturing, tissue cutting or tissue flap removal. Image-guided navigation is also a topic of intense interest in contemporary research.

4. Methodology

A systematic search in various scientific collections, like Clarivate's Web of Science Core Collection or SCOPUS was conducted to explore the use of artificial intelligence in surgical robotics, with a particular focus on neurosurgery. The search query for topic search (TS) used was:

$$TS = ((AI\ OR\ "Artificial\ Intelligence")$$
$$AND\ (Robot*) AND\ (surg*\ OR\ operation)$$
$$AND\ (Neuroscience\ OR\ Brain\ OR\ Neurology))$$

By including the terms "AI" or "Artificial Intelligence," it was ensured an extensive coverage of the relevant literature and highlighted the central role of this concept in our study. Using "Robot*," we captured all derivative forms of the term to explore the diverse applications of robotics in surgical procedures. Additionally, terms such as "surg*" or "operation" were essential to focus on various surgical interventions. The inclusion of the words "Neuroscience," "Brain," or "Neurology" was necessary to direct the research toward the field of neurosurgery.

The articles selected after a complex search were analyzed in terms of the specific technology, focusing on its benefits and challenges. This approach allowed to identify the need for further research and development on the topic. Comprehensive insights were gathered by examining the advantages demonstrated through findings, experiments, or measurements, along with observations related to limitations, challenges, dependencies, and other concerns. Additionally, future directions, recommendations, and related observations were also documented to guide subsequent efforts in the field.

5. Optimization of Neurosurgical Procedures

The implementation of AI and robotic technologies in neurosurgery brings a range of significant benefits, transforming both the way surgeries are conducted and the surgeon experience, with an impact in the preoperative, operative, and postoperative phases [19].

An essential aspect of AI use is its ability to provide an objective interpretation of clinical data [19]. This translates into a higher standard of safety compared to traditional human-performed interventions [8], [15], [20], as AI algorithms can identify and analyze information with superior accuracy [14], [15], [19], [20], [21], [22], [23].

The increased precision in surgical interventions is one of the most notable benefits brought by the use of artificial intelligence and robotic technologies in neurosurgery [2], [14], [15], [20], [22], [24], allowing surgeons to reach neural structures with exceptional accuracy [24]. This enhanced precision also contributes to reducing the invasiveness of surgical procedures, minimizing trauma to surrounding healthy tissues, and reducing the risks associated [8], [19] with traditional surgeries. Less invasive and more precise procedures help lower postoperative complications, such as infections [15], and accelerate patient healing, providing a safer and less painful experience [2], [20]. Moreover, implementing these modern technologies significantly reduces the time required for interventions, thereby improving the overall efficiency of the surgical process [14], [15], [19], [20], [21], [23]. The lower rate of postoperative infections, thanks to increased precision and safety [14], [15], [20], underscores the benefits of these technological advancements. This optimization of surgical procedures not only shortens the duration of operations and recovery but also translates into lower costs for patients and the healthcare system [20], [22], as increased efficiency can eliminate the need for additional or complicated procedures [2], [8]. Thus, another notable benefit is the reduction of costs associated with diagnostics and treatments [2], [14]. The use of AI and robotics can optimize resources, facilitating broader access to quality medical services, especially in resource-limited regions [20], [21]. These advancements are essential, as patients benefit from a less stressful and more comfortable medical experience, with faster recovery times, ultimately improving their quality of life [2], [20].

For doctors, another significant advantage of using AI is the ability to enhance their technical skills. AI-based pre-procedural simulations can help improve doctors' performance and reduce the invasiveness of surgical interventions [20], [22]. This is achieved through real-time monitoring of surgical performance, allowing doctors to quickly identify and correct any deficiencies [22], while also assisting doctors in selecting the ideal treatment protocols [14]. Thus, the use of AI in neurosurgery can improve the efficiency of the surgical team and reduce the cognitive burden on surgeons. With AI algorithms assisting in real-time decision-making, the workflow in the operating room becomes more streamlined [25], allowing surgeons to focus more on critical tasks without being overwhelmed by repetitive or urgent decisions [19], [23]. This support is particularly valuable in managing complications during surgery, where AI systems can predict potential issues based on historical data and provide solutions to prevent critical errors [14], [21], [22], [25]. As a result, these systems help maintain surgical precision even when human concentration may wane, ensuring a consistent level of care throughout the procedure [2], [8], [21]. AI allows surgeons to work more comfortably for extended periods, improving overall performance and reducing the risks associated with surgeon fatigue, ultimately leading to higher success rates in complex neurosurgical interventions [2], [14], [15], [20], [23].

Furthermore, the integration of AI and robotics significantly enhances surgical planning by providing detailed information through imaging technologies such as MRI and CT (Computed Tomography) scans. AI-based image recognition tools can accurately identify critical anatomical features and abnormalities, guiding surgeons through complex procedures and helping them avoid damage to sensitive structures [14], [19], [25], such as small corridors. These capabilities lead to a more personalized approach to surgeries, where the unique anatomy of each patient is considered, reducing the risk of unintended complications [14], [20], [23]. This precision also ensures that critical areas are more efficiently targeted in minimally invasive interventions [20], affecting less healthy tissue and resulting in faster patient recovery [8], [19], [21].

In conclusion, the integration of artificial intelligence and robotics in neurosurgery brings essential benefits, from increased precision and efficiency to improved accessibility and patient experience. These advancements not only transform the surgical act but also reshape the entire dynamic of the relationship between patients and the healthcare system, promising a safer and more efficient future in neurosurgery.

6. Limitations

The implementation of AI and robotics in neurosurgery offers multiple advantages but comes with significant limitations. These are analyzed in the context of human resources, technical aspects, and associated costs.

One of the primary challenges in using AI and robotics is human supervision. Even though AI can manage complex tasks, there is a constant need for human monitoring [2], [8], [21], [23] to avoid errors that may arise from technical malfunctions. AI systems in neurosurgery, for example, while capable of enhancing precision and reducing the risk of human error, still require a human operator to supervise the procedure and intervene in case of technical problems or misinterpretations [20], [21]. This necessity is often underestimated, but the essential role of the human factor cannot be neglected in the context of neurosurgery, where the consequences of an error can be devastating. Advanced robotic systems, although able to perform delicate surgical tasks, require constant oversight to prevent potential calculation or implementation errors [21], [25]. AI cannot function entirely autonomously, at least at the current stage of technology. While AI can improve efficiency and reduce the physical and mental burden on physicians, its implementation still requires the presence of a qualified specialist to monitor and adjust system parameters according to the evolution of each case [8], [25]. In many complex procedures, human assistance remains essential to ensure patient safety and to make necessary adjustments during the intervention [19].

Another major challenge is the initial resistance from medical staff [20], [21], [24], as well as from patients [2], [20], regarding the widespread use of AI and robotics. Many professionals in the field may feel that reliance on technology could diminish the development of their manual and cognitive skills [21]. Additionally, patients may show reluctance to fully entrust an AI system [21], even if it offers tangible benefits such as increased accuracy and a reduced risk of postoperative infections [2]. This resistance is not limited to surgeons or physicians but can also be found at the level of hospital management or even health policies that may delay the adoption of these technologies [19], [22].

From a technical standpoint, hardware and software malfunctions represent one of the greatest threats in the use of AI and robotics in surgery. Complex robotic neurosurgery systems, for example, are exposed to the risk of technical errors that can affect both performance and safety during interventions. In particular, calibration errors or malfunctioning sensors can lead to misinterpretations of clinical data or incorrect positioning of surgical instruments [21]. Moreover, machine learning algorithms are at risk of overfitting, which can lead to incorrect predictions during surgical procedures [21], [25]. This underscores the vulnerability of AI-based systems to technical errors, which can have serious consequences for patient safety.

The quality and accuracy of AI systems are also limited by the available technological resources. While AI can enhance precision and reduce errors, there are times when they do not achieve the desired level of accuracy due to technical constraints such as processing latency or measurement errors [15], [25]. These technical limitations are particularly exacerbated in fields such as neurosurgery, where any deviation from the established path can have critical effects on patient health [14], [20]. Although steady progress is being made towards alleviating these issues, they remain a major concern for medical teams relying on these systems for high-precision interventions [24].

Safety and legal aspects represent another set of significant limitations in the use of AI in neurosurgery. AI technologies must be regulated and validated through strict protocols to ensure that no additional risks to patients arise. Due to the complexity of these systems, any error, no matter how minor, can lead to complex legal ramifications. If a robot makes a mistake, who is responsible? This is a topic of debate among specialists in ethics and medical law [2]. Additionally, the risks associated with the limited autonomy of AI systems impose further safety measures to avoid potential incidents [19], [21].

Costs represent another barrier to the widespread implementation of AI and robotics in neurosurgery [14]. The acquisition and maintenance of these systems are extremely costly [15], [19], [21], and these initial costs are difficult to bear for many hospitals and clinics, especially in less developed regions [20], [21]. In addition to these direct costs, there are also indirect costs related to staff training and adapting existing infrastructure to accommodate new technologies [14], [20], [24]. These investments are not always justified, especially in situations where the technology is used only for a limited number of procedures [20]. For instance, robotics for brain biopsies, a specific procedure, requires highly specialized equipment, the acquisition and maintenance of which pose significant financial challenges [20].

Maintenance costs are also significant. Once implemented, AI systems require constant maintenance and regular software updates to ensure optimal functioning [21]. Furthermore, disruptions caused by technical malfunctions or the need for repairs can lead to costly delays in the medical schedule [24]. These malfunctions can affect the quality of services provided and create logistical difficulties [20].

Another important aspect is the knowledge base required for the implementation of these technologies. AI technology, in the field of neurosurgery, requires access to an enormous volume of data to improve and function properly. However, access to the necessary data is often restricted due to privacy concerns, and the collection and management of such data is a complex process [21]. Additionally, the development and standardization of systems that enable interoperability between different AI technologies are still in their early stages [22], making the widespread adoption of these solutions more challenging [20].

Technological complexity represents another major challenge. The implementation and operation of AI and robotic systems require a high level of technical expertise from the medical staff [23]. This not only involves continuous training but also adaptation to new technologies as they evolve [20]. Even the most advanced AI systems require a well-defined software architecture, along with mechanical and imaging systems, in order to function optimally [22]. In the absence of these integrated solutions, the efficiency and safety of these technologies could be compromised.

Thus, although AI and robotic technologies offer undeniable advantages, such as increased precision and reduced operation times, their limitations are complex and often difficult to overcome, complicating the widespread adoption of AI in neurosurgery. These considerations reinforce the importance of a cautious and well-planned approach for adopting AI in the field of neurosurgery.

7. Future Research Directions

Future research directions in the field of AI-assisted and robotic neurosurgery are essential to maximize the benefits of these technologies and overcome current challenges. A key aspect focuses on confirming the functionality of algorithms through the use of validation samples and independent datasets [21]. This will ensure that AI systems are not only effective in controlled conditions but also in various clinical applications, thereby enhancing the reliability and trust in these technologies in critical surgical environments.

Additionally, the development of strict ethical regulations is indicated to prevent abuse and manipulation of human behavior, especially in the context of critical decisions in neurosurgical treatments [21]. It is essential that ethical frameworks evolve in parallel with technological advancements to ensure patient welfare and maintain the integrity of medical practice.

The use of AI to improve clinical decision-making processes is another essential research direction. AI-based systems could rapidly provide updated information for medical professionals, helping them access a vast library of previously performed similar surgical interventions [2]. This could enhance not only the efficiency of interventions but also the quality of patient care.

Multidisciplinary collaborations are becoming increasingly important, facilitating the integration of various perspectives and expertise in developing innovative solutions [19], [21]. One of the recommendations refers to data analysts [19]. These collaborations are crucial to ensure a holistic approach to the complex problems encountered in neurosurgery.

Collaboration between physicians and robots is essential to improve the accuracy of surgical interventions, considering the challenges related to the high rate (66%) of false positives in the diagnosis of strokes [14]. This underscores the necessity of constant human oversight, given that AI systems may present errors in assessing patient conditions [14]. Moreover, it is important to develop advanced software tools that support 3D visualization.

Integrating AI into medical and surgical training represents a promising direction. The use of AI technologies in simulations could improve the technical skills of future physicians, increasing their comfort level during surgical interventions [22].

Another significant research direction is the improvement of recording techniques and the development of control algorithms that can optimize human-robot interaction. These systems could provide real-time guidance to surgeons, indicating correct trajectories and assisting in decision-making in complex situations [20], [25]. Advances in wearable sensor technologies could extend research in human cognitive processing, allowing multisensory interactions with the environment and thus enhancing robotic performance during procedures [22].

The use of AI could also be expanded to tackle not only surgical interventions but also neuromuscular and neurodegenerative diseases [15], [21], which are currently managed through medication and deep brain stimulation. This expansion could facilitate the development of personalized treatment approaches, tailoring therapies to the individual profiles of patients and thus improving the overall efficiency of treatment [21].

In the long term, advancements in the fields of robotics and AI could completely transform the landscape of neurosurgery. It is important that all these innovations are implemented in a way that ensures patient safety and adheres to ethical standards, thereby building trust among both medical staff and patients [19]. This proactive approach will enable successful integration of advanced technologies and will also contribute to improving the quality of healthcare provided, with the ultimate goal of enhancing therapeutic outcomes and the patient experience.

8. Conclusions

The integration of artificial intelligence and robotic technologies in neurosurgery marks a significant transformation in how surgical interventions are performed, having a profound impact on patient safety, operational efficiency, and the quality of medical care. The use of these advanced technologies has demonstrated an increase in precision during surgical procedures, minimizing trauma to healthy tissues and reducing the risks associated with postoperative complications.

However, the widespread adoption of these innovations is accompanied by considerable challenges, such as the need for constant human supervision, resistance from medical staff and patients, and the technical complexity of the systems. These limitations underscore the importance of careful and well-regulated integration of artificial intelligence into neurosurgical practice to ensure the safety and efficiency of interventions.

Additionally, the future of research in AI-assisted neurosurgery should focus on algorithm validation, the development of strict ethical regulations, multidisciplinary collaboration, and the integration of AI technologies into medical training. These research directions aim to enhance the clinical decision-making process, optimize human-robot interaction, and personalize treatments for patients.

In the long term, continuous advancements in robotics and artificial intelligence could radically transform the landscape of neurosurgery, improving the quality of care and therapeutic outcomes. It is crucial that these innovations are implemented responsibly, adhering to ethical standards and thereby ensuring trust from both medical staff and patients.

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