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Editorial

Robotics in neurosurgery: An overview

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1. Introduction

Neurosurgery, known for its precision and complexity, has seen transformative advancements with the integration of robotic systems. Since the mid-1980s, when the PUMA 560 robot was first used for stereotactic biopsies, robotics have improved surgical accuracy, reduced invasiveness, and minimized human error.[1-3] Soon after, the PUMA 200 was used in guiding biopsy needles and tumor resections. With the rise of AI and machine learning, surgical robotics became more intelligent and precise.[4] The NeuroMate, the first FDA-approved robotic device specifically for neurosurgery, marked a breakthrough. Today, robotic systems are commonly used in spinal instrumentation and brain procedures, though challenges such as high cost and limited tactile feedback remain. Still, robotics continue to revolutionize neurosurgical practice.

1.1. Classification of robotic systems in neurosurgery

Robotic systems in neurosurgery typically include key components like sensors, a computing unit, controllers, actuators, and imaging interfaces. These systems are broadly classified into three types:

1.1.1. Telesurgical robots (Master-Slave)

These systems allow remote operation by the surgeon. A prime example is the 'NeuroArm', developed in Canada, which is MRI-compatible and offers haptic (tactile) feedback. It replicates human hand movements with eight degrees of freedom (DOF) and allows surgeons to operate remotely using real-time video and touch-based feedback. It has been successfully used in over 1,000 neurosurgical procedures, such as tumor resections and biopsies.[5]

1.1.2. Surgeon-supervised systems

These robots execute pre-planned tasks under the direct supervision of the surgeon. Early examples include the PUMA and Minerva robots. More advanced platforms like SpineAssist and Renaissance (Mazor Surgical Technologies) are widely used in spinal surgeries and are expanding to cranial applications. In these systems, the surgeon plans the trajectory, and the robot executes it with high precision, while the surgeon oversees the process.[2,5]

1.1.3. Shared-controlled systems

In this model, the robot and surgeon work together. The surgeon manipulates the tool, while the robot provides stability and tremor suppression. An example is the Steady Hand System from Johns Hopkins, which allows refined motion during delicate brain operations. Other systems like the NeuRobot and Evolution 1 support tasks like endoscopic surgery and tumor resections with precise coordination and tool control.[6]

1.2. The evolution of robotics in neurosurgery

Robotics in neurosurgery began with the goal of enhancing precision and minimizing human error. Early robotic systems were limited in scope, mainly assisting with stereotactic biopsies or electrode placements. Over the past two decades, technological advancements have introduced sophisticated

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systems capable of performing complex neurosurgical procedures with minimal invasiveness and high accuracy.

Prominent robotic systems in neurosurgery include:

1.2.1. PUMA-200

Introduced in 1988, it was one of the first robots used in neurosurgery. With six joints mimicking human arm movement, it guided stereotactic biopsies and electrode placements with excellent stability.

1.2.2. NeuroMate

Developed in 1987, it remains widely used for deep brain stimulation (DBS) and biopsies. With six DOF and sub-millimetric accuracy, it supports both frame-based and frameless procedures.[6]

1.2.3. NeuroArm

Built in 2001, it was the first MRI-compatible, image-guided robotic system. Featuring tremor suppression, motion scaling, and micron-level accuracy, it is ideal for microsurgery. The arms are built from non-magnetic materials to operate safely within MRI environments.

1.2.4. ROSA

The ROSA system assists in both cranial and spinal surgeries, offering real-time navigation and precision. It integrates preoperative imaging with intraoperative guidance and is used for DBS, biopsies, and tumor resections. Its touchscreen interface and versatility make it a powerful modern surgical tool.

1.2.5. da Vinci system

Widely used in urology and gynecology, the da Vinci system offers enhanced visualization and precision but is less used in neurosurgery due to limitations in tactile feedback and miniaturization. However, research is ongoing to adapt it for brain surgery.

1.2.6. NeuRobot

Designed for microneurosurgery, it includes a master-slave setup with micro-dissecting tools and a 3D endoscope. It has been used in minimally invasive tumor resections and endoscopic brain surgeries.[6,7]

1.2.7. Mazor systems (SpineAssist, Renaissance, Mazor X)

These systems have revolutionized spinal surgery. Starting with SpineAssist in 2004, Mazor introduced real-time 3D navigation and CT-guided planning. The newer ‘Mazor X Stealth’ Edition combines advanced software, real-time feedback, and robotic precision, and is expanding into cranial applications.

1.2.8. Pathfinder

Developed by Prosurgics, the Pathfinder supports frameless stereotactic procedures like biopsies and electrode placements. It integrates imaging-based planning and neuronavigation for precise interventions.

1.3. Benefits of robotics in neurosurgery

1.3.1. Enhanced accuracy

Robotic systems provide sub-millimetric accuracy in placing tools and performing tasks, essential for procedures like DBS, spinal screw placement, and biopsies.[8]

1.3.2. Tremor suppression & motion scaling

Systems like NeuroArm eliminate tremors and convert large hand motions into micro-movements, ideal for delicate surgeries.

1.3.3. Minimally invasive surgery

Smaller incisions lead to less trauma, reduced pain, quicker recovery, and fewer complications. Robotics enable precise navigation even in deep-seated or hard-to-reach areas.

1.3.4. Advanced visualization

3D imaging, real-time MRI/CT integration, and augmented reality help visualize complex anatomy and guide tools with confidence.

1.3.5. Remote access and telesurgery

With robotic telesurgical systems, expert surgeons can operate remotely, expanding access to specialized care in underserved regions.

2. Challenges and Limitations

3.1. High cost

Acquisition, maintenance, training, and software updates are expensive. Many smaller hospitals struggle to afford robotic systems.

3.2. Training requirements

Surgeons and staff must undergo extensive training. The learning curve can impact initial outcomes and surgical efficiency.[3-8]

3.3. Limited neurosurgical tools

Many robotic tools are designed for general surgery. There is a need for more microsurgical instruments tailored specifically for brain and spinal procedures.

3.4. Tactile feedback issues

Despite progress, robots still don’t replicate the nuanced tactile sensations of manual surgery, which are critical in delicate dissections.[1-3]

3. Integration Challenges

Compatibility with existing hospital systems (imaging, navigation, patient records) can be difficult. Technical glitches also pose risks during surgery.[5-8]

4. Future Outlook

The future of robotics in neurosurgery is promising. AI will enhance decision-making and real-time error correction. Miniaturized robots and soft robotics will navigate tighter brain regions with minimal risk. Improved haptic feedback and telesurgical capability will allow more precise control and global surgical collaboration. As systems become more affordable and better integrated, robotic-assisted neurosurgery will become standard for many complex procedures, offering safer, faster, and more effective treatment.

5. Conclusion

Robotic systems are transforming neurosurgery by offering unparalleled precision, reduced invasiveness, and better patient outcomes. From early systems like PUMA-200 to advanced platforms like ROSA® and Mazor X, technology continues to evolve. While challenges like cost and feedback limitations remain, ongoing innovations in AI, instrument design, and system integration will drive wider adoption. Robotics is not just the future of neurosurgery—it is rapidly becoming its present.

6. Conflict of Interest

None.

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