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Robotics in neurosurgery: A literature review

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Abstract

Robotic surgery has been the forte of minimally invasive stereo-tactic procedures for some decades now. Ongoing advancements and evolutionary developments require substantial evidence to build the consensus about its efficacy in the field of neurosurgery. Main obstacle in obtaining successful results in neurosurgery is fine neural structures and other anatomical limitations. Currently, human rationalisation and robotic precision works in symbiosis to provide improved results. We reviewed the current data about recent interventions. Robots are capable of providing virtual data, superior spatial resolution and geometric accuracy, superior dexterity, faster manoeuvring and non-fatigability with steady motion. Robotic surgery also allows simulation of virtual procedures which turn out to be of great succour for young apprentice surgeons to practise their surgical skills in a safe environment. It also allows senior professionals to rehearse difficult cases before involving into considerable risky procedures.

Keywords: Robots, Neurosurgery, Precision, Minimally invasive, Simulation.

Introduction

Robotics revolves around minimally invasive stereo-tactic surgery with or without the addition of endoscope; with robots being extensions of computer systems that allow for programme to interact with humans in a medical setting¹ allowing for greater precision, delicacy and improved capabilities of surgeons while performing procedures. The initial application of robotics in neurosurgery was for biopsy. Neurosurgery may have been the pioneer in robot assisted surgery but due to anatomical constraints the idea of robotic surgery has been extended to other fields such as, urology, gastroenterology, etc. The major constraints of advancements of robotics in neurosurgery are anatomical limitations, delicate neural structures and minimal scope

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for progress. Current system labelled robots more precisely as co-robots or "cobots" as they function in association with human operators rather than working autonomously.² The growth and development has been immense in past two decades. In 2015, over 700,000 surgical procedures were performed using da vinci system.³

Robotic surgery can be classified on the basis of working environment, manipulator design, targeted structure and methods or the level of autonomy.⁴ For better understanding, it is generally classified into active and passive systems.⁵ The passive system, also described as the master slave relationship,⁶ being one in which the robot is the passive entity with the surgeon manipulating the physical tool. Meanwhile, the active system provides robots with a much greater degree of autonomy with the surgeon intervening only if and when necessary.⁷ The intermediate form of these two systems is the semi-active system in which the robot offers some guidance to the surgeon performing the procedure. For example, the neuromate system.⁶

The classification according to surgeon robot interaction includes three models: 1) the supervisory controlled system in which the robot performs actions based on a surgical plan which is made using computerised axial tomography (CT)-scans or magnetic resonance imaging (MRI) brain of the patient. 2) Tele-surgery system uses a haptic system interface in real time where the robot replicates the surgeon's movement from the interface. 3) Shared control system is a symbiotic system where the surgeon has full control and the robot assists in hand manipulation of the instrument.⁸

Review of Evidence

Different types of devices depending on their function, design or level of autonomy are used in different surgical procedures. The robots includes Puma 200, Neuromate, Pathfinder, Neuroarm, The spine assist, Renaissance, Steady hand system, Neurolocate, iArmS, Expert, Spinal robotics, Isys1 ROBOT, Augmented reality systems, Neurosurgical lasers.⁹

Puma 200: First used 30 years ago to perform a stereo-tactic surgery where a CT guided biopsy needle was

placed in the brain.¹⁰

Neuromate: It is a stereo-tactic system with 6 degrees of freedom. It was first developed in 1987. It is used in several neurological procedures including deep brain stimulation and stereoecephalography. In clinical settings it is considered as a safe instrument for biopsies.¹¹

Pathfinder: A stereo-tactic system that has six degrees of freedom.¹² Pathfinder works with an accuracy of sub-millimeter making possible operations too delicate to be done by surgeons such as correcting Parkinson disease by correct application of current to stop tremors.

The neuromate and pathfinder are both systems possessing six degrees of freedom, such devices use reflectors attached to the head of the patient using a camera system instead of radiological, ultrasonographic or mechanical guidance.¹²

Neuroarm: Developed in 2001, it is one of the most refined neurosurgical master-slave system to date. It is a telesurgery system that allows the surgeon to perform while in a location other than the operation room.¹³ It has the benefitting ability to be able to perform stereo-tactic and microsurgical procedures with real time MRI.¹⁴ It was built to bear within strong magnetic fields allowing for high quality MRI intra-operatively without having to interfere with the procedure.¹⁵ The system is capable of performing needle insertion, cutting, cauterisation and irrigation microsurgically while simultaneously obtaining an MRI. It can also perform microdissection, thermo-coagulation and fine suturing along with procedures such as lesionectomy and aneurysm clipping. The robot was designed to be able to mimic the position and tool manipulation of surgeons during surgery a process known as biomimicry. In 2008, brain lesion of a 21-year-old patient was removed using the neuroarm for the first time.^{16,17}

Spineassist: It was approved by the Food and Drug Administration (FDA) in 2011. Considered to be the pioneer neuro-robot in minimally invasive surgery.¹⁸ Device is designed to offer least invasion, complication rates and recovery time and may also contain an option for fluoroscopic guided surgery.¹⁹ It is a bone-mounted hexapod miniature robot. It is firmly connected to patient's body through one of the three platforms; a clamped bridge attached to spinous process, a Hover-T bridge attached through three pins to patient's bony anatomy or a bed mount device with only one pin connecting the Hover-T bridge to the patients' spine.⁸ Spineassist is used in drilling as well as for thoracic and lumbar pedicle screw insertion procedures.²⁰

The basic mechanism behind spine assist is its ability to limit the surgeon's natural full range of motion from six degrees of freedom to two degrees of freedom, thereby helping to bring the surgeon to a pre-defined point of the anatomy at a precise trajectory which is based on the pre-operative plan. One has to take into account possible human and mechanical error such as that associated with distraction as well as changes between supine patient in preoperative CT and patient prone on the operating table. Robotic navigation plays a key role especially in cases of minimally invasive surgery and cases where the anatomy presents a challenge.^{19,21-28} However, there is currently only one CE-FDA approved product in the market coupled with scanty scientific publications making these the drawbacks of this product.

Renaissance: Image-guided new generation system based on spine assist for keyhole neurosurgery.^{29,30} It is directly mounted onto the patient's skull with the help of four pins. Renaissance uses an automated mechanical guide based on a trajectory that has been predefined with preoperative CT/MRI-based plan to support keyhole drilling, insertion of a needle, probe, catheter etc.

Steady hand system: This system is designed to filter out unnecessary hand movements such as tremors, allowing the surgeon to have familiar feel of surgery with robotic precision. It is the only shared-control system used in micro-neurosurgery.³¹ Due to limited research on this system its use has mostly been restricted to retinal micro-surgery.³²

Neurolocate: Stereo-tactic robot that is basically a fiducial marker mounted on a robot arm during intraoperative x-ray/CT. Neurolocate system is both time and cost effective with its intra-operative imaging abilities. It also minimises procedure time with increased patient comfort. Increased flexibility of the patient head position due to the adjustable nature of the fiducial marker frame; Compatible with existing frame systems for holding the patient head

iArmS: The term stands for intelligent arm-support system, a revolutionary medical robot developed as an operation support robot which automatically follows the surgeons hand movements seamlessly. It is designed in such a manner that it supports and prevents surgeons hand from trembling and fatigue during microscopic surgery.³³ Neurosurgery is a field that demands ultra fine dexterity and manipulation of surgical tools within the narrow constraints of the brain anatomy. Owing to this fact, neurosurgery is very time consuming. The iArmS system is built to allow surgeons to carry out extensive procedures for an extended period of time by minimising

hand tremors and fatigability. It is particularly useful in endoscopic procedures such as endoscopic endonasaltranssphenoidal surgery (ETSS) for pituitary tumours and midline skull base lesions.^{34,41}

EXPERT System: Micro neurosurgery requires the surgeon to perform with a high level of precision. This system acts like an intelligent arm rest, possessing five degrees of freedom, the robot follows the surgeon's arm and attaches at an adequate position automatically. The surgeon does not need to look away from his microscope to change the position of the armrest allowing him to multitask. The EXPERT system is similar to iArmS to markedly decrease hand tremor and fatigability.³⁹

iSYS1 Robot: In a pre-clinical phantom trial conducted using the iSYS1 systems to assess the accuracy and duration in needle positioning done robotically versus manually. It was found that the iSYS1 systems had far greater accuracy; shorter setup time, and shorter instrument positioning time. The robot also displayed a shorter learning curve.⁴²

Spinal robotics: The application of robotics to spinal surgery has made it more minimally invasive reducing the need for extensive procedures. Use of robots has also dramatically increased the accuracy of the procedures performed with a marked decrease in the amount of radiation that both patient and surgeon were previously exposed to.⁴³ The published data regarding benefits of minimally invasive surgery (MIS) over open approach has made a compelling case for distinct clinical benefits as it reduces blood loss, extent of hospital stay, rehabilitation and postoperative patient discomfort.^{44,45} In order to operate in a competent manner surgeons are required to rely on imaging, navigation and guidance technologies due to restricted field of view in MIS. To facilitate surgeons performing MIS newer and far more advanced navigational systems have been developed. These systems act as safety nets delivering results at par with extremely experienced surgeons.^{22,46,47} Computer-based navigation systems were first brought to the field of spine surgery in 1995. Although they have already become familiar in cranial procedures such acceptance in spinal surgery is yet to be seen.^{48,49} Spinal surgery and neurosurgery are seen as the perfect frontiers for incorporation of robotic assisted surgical procedures.^{20,50}

Augmented Reality Systems: It is an image guided neurosurgery system with intraoperative applications. It is used to project images onto the patient's head, skull or brain surface in real time aiding in MIS procedures. This allows surgeons to use direct visualisations resulting in increased efficacy.⁵¹ Virtual reality systems have been

developed for allowing younger surgeons to practice complicated procedures with the help of robots such as the neurobot and the neuroarm. This can be done for replication of virtual anatomy and even for remote cadaveric surgical assistance.^{52,57}

Neurosurgical Lasers: Even though there has been significant increase in precision and accuracy laser technology, it is still not practiced on a wide scale. Owing to the advancements made in laser technology, if there is proper collaboration of laser technology with neurosurgery it could provide an ideal platform for neurosurgical applications.⁵⁸

Neurosurgery is one of the most integral fields for the application of medical robotics. The main reasons for this are as under:

- 1) The brain is present within a solid container in the form of bony skull thus making it feasible for the devices to be positioned on skull during procedures. This is especially true in adults and older children.
- 2) The functional somatotopy and anatomical topology usually correspond well to each other.
- 3) Of all the organs of the body, brain has the most complex anatomy and requires the highest degree of precision. Stereo-tactic procedures have made this precision possible with their minimally invasive routes. For these procedures with high precision robotics is becoming an essential tool.

Current robots work in co-ordination with human operators merging into one the advantages of human thinking with the ability of robots to provide data, superior spatial resolution, geometric accuracy, superior dexterity, faster maneuvering and non-fatigability with steady motion. Robots are able to reduce human hand tremors from 40 micrometre to around 4 micrometre due to inbuilt dexterity enhancement techniques.⁸ Robotic systems although are able to work at a much higher degree of precision with much less damage to the brain than a human could possibly perform, they still are not meant as a replacement to surgeons. Humans and robots are meant to exist in symbioses each benefiting other in a harmonious ecosystem.¹

With the advent of the modern era and introduction of robotics in neurosurgery new frontiers have been opened in the field, however, they have also brought along with them a host of new challenges. The most significant of them is cost-effectiveness. Recent studies suggest that a large bulk of the increased cost was associated with the initial amount needed to purchase the robot which was

estimated at \$1,200,000 as well as the yearly amount required for the maintenance which was estimated to be around \$100,000. Other drawbacks include the weight and size of the machinery in use as well as lack of tactile and force feedback.¹ Robots are highly specialised machines whose usage demands a certain degree of mathematical literacy. This requires the training of staff including doctors and nurses in the new art, which is time as well cost demanding.⁸ Moreover, increased space requirements are needed to fit a robot in the operating room. Technical failures of robots can be fatal to patients in critical conditions.⁶

Da Vinci: Da Vinci robotic surgical system offers the surgeon seven degrees of freedom. The latest version of this system is equipped with HB imaging system, three operating arms, training console for a second surgeon and modifications for minimally invasive surgeries.⁵⁹

SOCRATES: It is a tele-collaboration system that allows the global communication of one surgeon with another

from remote operating station to control the operating arms. It uses telestrator to annotate anatomical and surgical directions and it too can share audio and video of operating room to collaborate with another surgeon. Six different cases (five craniotomies and a lumbar puncture) were reported in which this technology was used. No surgical complications were found with this procedure.⁵⁹

ROSA: The robotic stereotactic assistance has a robotic arm of six degree freedom which allows precise alignment of multiple trajectories for the placement of electrodes.⁶⁰ After its recent FDA approval, Sumeet. V et al reported the first case of deep brain stimulation implantation in which this frame-based technology was used.⁶¹

Robots and humans work in synchronicity in the field of neurosurgery to combine the advantages from both man and machine into one super precise, dexterous model. Surgical simulation includes virtual procedures that include visual, audio, tactile and other feedback. This allows young apprentice surgeons to practise procedures

Table: Salient features of different robotics in neurosurgery.

Procedure	Salient Features
PUMA 200 Da Vinci	CT- guided needle biopsy -7 degree freedom - HB imaging system -three operating arms
SOCRATES	-telecollaboration among surgeons in different parts of the globe. - can share audio and video
Steady-hand Surgery Neurolocate	-Filter out unnecessary hand movements -Fiducial marker -Intraoperative imaging abilities
Neuromate	-6 degrees freedom -deep brain stimulation -safe for biopsies
Pathfinder	-6 degree freedom - Accuracy of sub-millimeter for too delicate procedures.
Neuroarm	-telesurgery -Intraoperative MRI -Biomimicry
Spine Assist	-2-6 degrees freedom -Can perform fluoroscopic guided surgery
Renaissance iArmS	-New generation of spine assist for key surgery -Minimize hand tremors and fatigability -particularly useful for endoscopic procedures
EXPERT system	-similar to iArmS with improved functioning -5 degrees of freedom
iSYS1 Robot	-Improved instruments positioning -Shorter setup time
Spinal Robotics Augmented Reality System	-Increase accuracy of procedures -Image guided surgical system -Provide virtual reality system for young surgeons to practice.
Neurosurgical Laser ROSA	-Increased precision and accuracy of laser technology. -allow 6 degree of freedom.

in a safe environment (Table).

Conclusion

To realise the full potential of robots in neurosurgery integration of systems, an increased effort is required towards compatibility of imaging software and planning software as well as end effectors. The emphasis is on building on past success and maximising the full potential of surgical robots in the future. The main stakeholders are surgeons, engineers, entrepreneurs and health-care administrators. Acceptance of the robotic medical manipulation will allow neurosurgeries to move past its challenges and enter a new sphere of development where robots will supplement not supplant surgeons and together they can perform better than either can individually.

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