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Surgical Robotics

Systems Applications and Visions

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Chapter 30
Robotics in Neurosurgery

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> *"Concern for man and his fate must always form the chief interest of all technical endeavors. Never forget this in the midst of your diagrams and equations"*
>
> – Albert Einstein.

Use of robots in surgery, especially in neurosurgery, has been a fascinating idea since the development of industrial robots. Using the advantages of a robot to complement human limitations could potentially enhance surgical possibilities, other than making it easier and safer. Over the last few decades, much progress has been made in this direction across various disciplines of neurosurgery such as cranial surgery, spinal surgery and radiation therapy. This chapter details the necessity, principles and the future directions of robotics in neurosurgery. Also, the concept of curvilinear robotic surgery and associated instrumentation is discussed.

The idea of using robots in surgery has fascinated surgeons since the making of the first robots for industrial and military use. The first robots were developed in the late fifties for use in industry mainly as transfer machines, used for transporting objects across a few feet. Further design modifications with articulated multi axial arms helped in the making of robots such as Stanford Arm and Programmable Universal Machines for Assembly (PUMA), which were used for automation of manufacturing processes.

Robotics in surgery has made giant strides in recent years with its increasing use in certain specialties like urology and gynecology. Use of the robot da Vinci (Intuitive Surgical, Sunnyvale, CA) for surgeries such as prostatectomy and hysterectomy, has come a long way from hype to hope, creating new benchmarks for surgical care [1]. Robots are also being researched and developed for use in other specialties like neurosurgery, cardiothoracic surgery, etc. The first instance of use of a robot in neurosurgery was in 1985 for stereotaxy, where an industrial robot (PUMA) was used for holding and orienting a biopsy needle (Kwoh et al. [20]).

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Since then, robotic applications have developed in safety and functionality. They have been tested and some practiced in neurosurgical procedures such as brain irradiation (using the CyberKnife), pedicle screw placement, navigation in neuroendoscopy, robotic frameless stereotaxy and even robotic or robot assisted microsurgery [2–4]. However, there still are a few large chasms that need to be bridged, for this giant technological leap to be seen as a standard of patient care in neurosurgery. This chapter focuses on the current state of robotic applications in neurosurgery, its current limitations, challenges in development and their future.

30.1 What is a Robot?

Robot is a programmable computer device with mechanical abilities to perform tasks, generally by interacting with the environment. As defined by the Robotic Institute of America, it is "a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or other specialized devices though various programmed motions for the performance of a variety of tasks." Generally robots used in medicine are made of multi-jointed links, which are controlled by a computer device. The end-piece or the end link of such a construct is called an "end-effector," to which attaches various instruments for performance of any desired activity. The end effector can have many degrees of freedom, which translates to the degrees of dexterity of the device.

Robots are indefatigable, accurate and have the ability to process a large amount of data simultaneously. They have the advantage of having near absolute 3-dimensional geometric accuracy apart from being able to be fast in performing their tasks with minimal or no tremor. Robots can reduce tremor of the surgeon's hand, from approximately 40 μm of the human hand to around 4 μm or less by dexterity enhancement techniques [5]. They can also be tele-controlled, thereby giving the advantage of remote operation. The disadvantages include lack of judgment and decision-making capacity, inability to spontaneously react to new situations, and poor spatial coordination, which are attributes of human performance.

30.2 Classification

There are many classifications of robots used in medicine. Broadly based on their usage Taylor classified them into (1) intern replacements (2) telesurgical systems (3) precise path systems (e.g. navigational systems) (4) precise positioning systems (e.g. stereotaxy system). Based on the type of the control system it is broadly divided into active and passive systems, though many robots would fit somewhere in the middle of this broad dichotomy. "Active" refers to the motion of the robotic device directed by a non-human device usually aided by a computer. The robot performs a part or whole of the surgical procedure autonomously. For example, ROBODOC (Integrated Surgical Systems Inc, Fremont, CA), used for hip replacement surgery, is an active system.

In a passive robotic system, the surgeon usually provides the input to move and control the device. A master–slave robotic system is an example of a passive system where the robot performs by constantly responding to the instructions of the surgeon.

Robots can also be semi-active, meaning they can provide guidance to the operator to provide the input for motion. For instance, navigational devices could help guide the surgeon in performing a stereotactic procedure. When using the NeuroMate, for example, the surgeon has complete control of the stereotactic procedure, but is aided by the guidance of the robotic device. Most of the robots used in neurosurgery are of this type wherein there is a "shared control system." The surgeon performs the procedure with the guidance of the robot.

30.3 Robots in Neurosurgery: What For?

Neurosurgery is a specialty which involves operating under a microscope for high precision and careful tissue handling. The brain is a 3-dimensional structure enclosed within the skull by rigid bone and easily damaged by even minor excursions of surgical instruments [6]. Human limits to safe tissue handling are a few hundred microns under the best of conditions, which is much more than the range of visual recognition with new microscopes. Such a discrepancy is due to the physical limitations of the human hand. Addressing this discrepancy with appropriate technological breakthroughs and innovation would help perform better surgeries.

Currently, numerous studies have been reported on the use of robots for specific surgical procedures, including robotic assisted pedicle screw placement, epilepsy surgery, robot assisted stereotactic procedures, and robotic brain irradiation.

30.4 Construction of a Robot

The construction of a robot essentially involves sensors and an operator console for acquiring information, a computer control system for processing information and the manipulator (base, links, actuators and end effectors) for task performance (Fig. 30.1).

The operator console is the interface between the robot and the input from the surgeon. It can vary from joystick or a finger glove to a voice operated system depending on the use of the robot and preference of the surgeon. Movements performed by the surgeon on the console can be scaled and reproduced in the end effector of the robot. By downscaling certain hand movements, the robotic arms can essentially eliminate tremor, thereby delivering only purposeful, intended motion.

Sensors are the other source for information input to the robot. Sensors may be vision or non-vision types [7, 9]. Vision sensors may be from optical fiber cameras mounted at desired locations; they may be mobile or fixed to a certain part of the

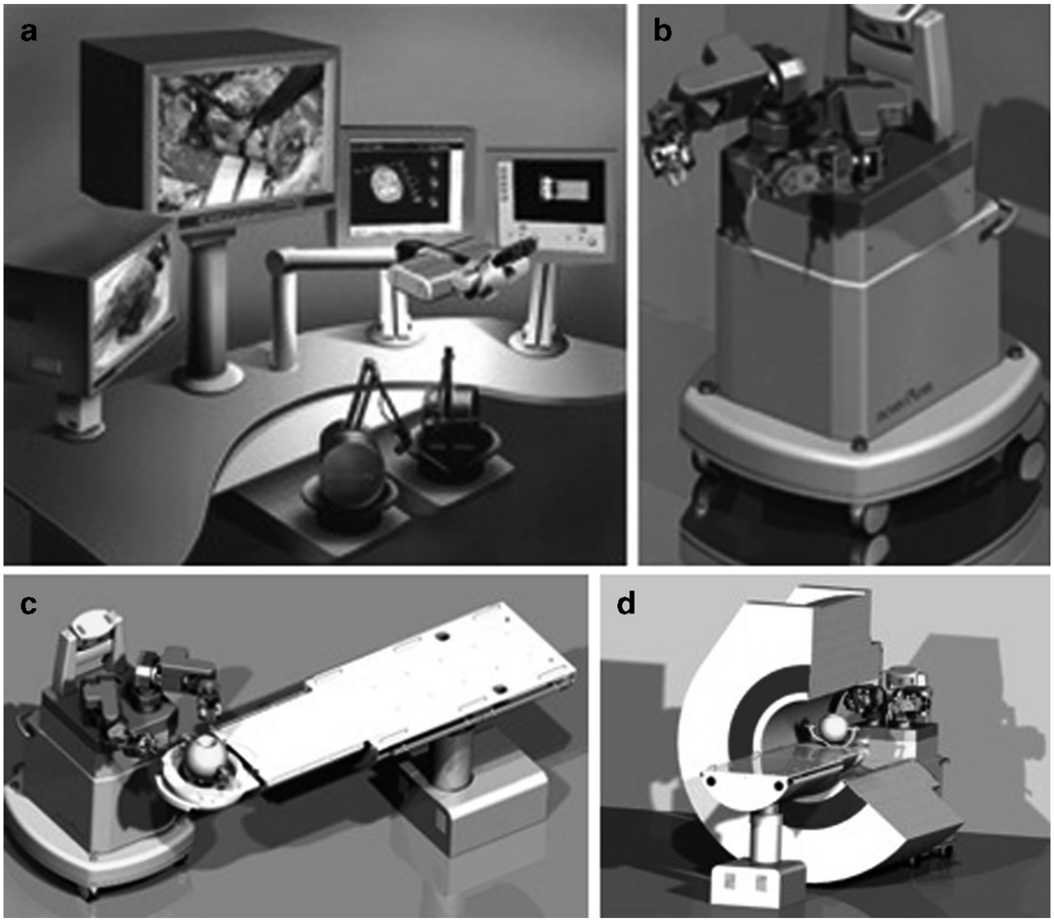


Fig. 30.1 (**a**) Picture showing the console of NeuroArm with video screen shots of microscopic view, external view of the head, and radiology images. (**b**) Structural design of NeuroArm with a base, joints, links and end-effector. (**c**) NeuroArm in position for performing microsurgery. Surgical microscope can be positioned adjacent to the robot's base. (**d**) NeuroArm attached to MRI machine for performing stereotactic procedures. (Pictures from Sutherland et. al. [7, 8])

manipulator. When fixed to the finger (end-effector) or wrist joint they can function as "eye-in-hand" devices. Non-vision sensors can process touch, pressure, temperature and object proximity. They also can provide information about the 3D positioning of the manipulator, thereby providing a feedback mechanism for the function of actuators. Haptic systems (from hapto in Greek, meaning "to touch") are sensors attached to actuators that provide force feedback from environment or virtual situations, thereby providing a real immersive physical feeling to the operator.

The computer system receives information from the sensors and operator interface (console) and processes it to direct the manipulator to perform the appropriate action. Often this computer interacts with multiple other computers, a mechanism that also allows for redundancy in the system in case of malfunction [7]. The computer system's ability to process vast amounts of data contributes to the ability of the robot to be precise in its actions. The software design for processing the information is a critical component in the efficiency of the robot. Basing the operating system of the robot on commercially available software packages may be an easy and attractive solution, and is done with most medical robotics projects. However, development of an original software tool based on the functional design of the robot and surgeons' need can also be a productive measure [10].

The manipulator is the mechanical component of a robot that consists of a base, links, end-effector(s), and the actuators. The end-effector is the final distal link where the action is performed. Actuators convert the signaling from the computer output into mechanical movements to position and orient the links of the manipulator. In image-guided surgeries like stereotactic procedures, the process of registration provides geometric inputs for the actuator (after being processed by the computer control system). The base helps in positioning the robot in a required place. The links are connected by joints, which in turn connect to the robot. The joints connecting the links can be either prismatic (meaning translation between joints possible) or revolute (able to rotate but not translate) [8]. Each joint denotes a degree of freedom. There could be numerous (up to six) joints in the design of robot. In such cases, the proximal three joints are usually the major joints, which determine the 3-D workspace (called work envelope) and the position of the end effector in space. The distal three joints determine the orientation of the object in space. The orientation is regulated by the junction of pitch, roll and yaw at the wrist (penultimate joint) [8].

30.5 Current Trends with Robots

Since the advent of medical robotics, robots have passed through a few stages of technological innovations. The first use of robots was for retraction purposes in surgery. This was followed by the use of robot named NeuroMate in surgical planning and for performing stereotactic procedures. However, these robots relied on preoperative images for positioning and lacked proper safety mechanisms. The first system to use real time guidance system was Minerva (University of Lausanne, Switzerland) which had an inbuilt CT scanner in its robotic arm. Following this, efforts to incorporate MRI robotic image guidance resulted in three different groups, from Harvard University, University of Tokyo, and the University of Calgary to develop them independently.

The development of individual robots has been targeted mostly to address specific kinds of procedures. The majority of the initial robots developed were for stereotactic surgeries, helping in positional 3D access accuracy. These include NeuroMate, Minerva and IMARL for precise needle insertion and biopsy, instrument holding and moving motion. Robots to help in open neurosurgery were developed later including the Robot Assisted Microsurgery Systems (RAMS) and the Steady hand system (Johns Hopkins University). RAMS was a master slave robotic arm with six degrees of freedom and equipped with tremor reduction technology such as motion scaling and tremor filters. Experiments to perform microanastomosis with this robot were performed in rats; the main disadvantage noted was it took twice the time compared to performance with hands. Robots also have been developed for radiosurgery for accurate delivery of radiation with out frame fixation, such as the CyberKnife for tumor resection endoscopic neurosurgery. Recent development of NeuroArm is a significant milestone in combining the abilities of stereotactic surgery and microsurgery in a single system with intraoperative real-time MRI navigation.

30.6 Robots for Position or Stereotaxy Based Procedures

Stereotactic procedures employ robotic systems for their near perfect accuracy in 3-dimensional space. The robot is used for the process of registration with CT/MRI images and trajectory planning to position a mechanical guide. Through the mechanical guide a surgical tool such as an electrode probe can be passed. NeuroMate is a standard robot used in stereotactic procedures that can reduce human error and save time in performing biopsies. This is a passive robotic system that guides the surgeon on the trajectory. It has five degrees of freedom and can hold tools such as electrodes or needles. The main disadvantage of this device is that it is bulky and occupies too much space in the operating room.

In patients with medically refractory epilepsy, surgical treatment with robots has been experimented and found to be a technically safe, feasible and an efficient procedure [11, 12]. For example, using SurgiScope, a handheld probe was jointly used with a stereotactic guide to accurately place subdural monitoring electrodes while the patients were undergoing craniotomy. Such accurate placement of the electrodes for recording the epileptic focus in the brain reduces the necessity to remove the frame or reposition the patient for further attempts [12]. Another robot called PathFinder (Armstrong Healthcare Ltd, High Wycombe, UK) was used in epilepsy surgery to locate the temporal horn and epileptic focus of the brain accurately. The device had a proximal link rotating in a horizontal axis and two links rotating in a vertical axis. An instrument holder that can rotate 180° is attached to the end of the arm (Fig. 30.2a). The system is registered to an MRI scan superimposed onto a CT scan with fiducials, and then attached to the Mayfield head holder [11]. After craniotomy, electrodes are passed into the hippocampus by the robotic device and a catheter is introduced into the temporal horn under image guidance from the robot. This system was found to be more accurate and less time consuming when compared to using a navigation system alone for such procedures [11].

A robotic stereotactic gamma radiation system named CyberKnife (Accuray, Sunnyvale, CA) has been used for precise irradiation of some brain and spinal pathologies such as tumors and arteriovenous malformation. This system, with the MRI registration of the patients head, avoids the frame usage in conventional gamma knife radiation techniques.

Robot assisted spine surgery studies for placement of pedicle screws (including trans-laminar facet screws, kyphoplasty and vertebroplasty) have been described [13, 14]. A commercially available system called SpineAssist (Mazor Surgical

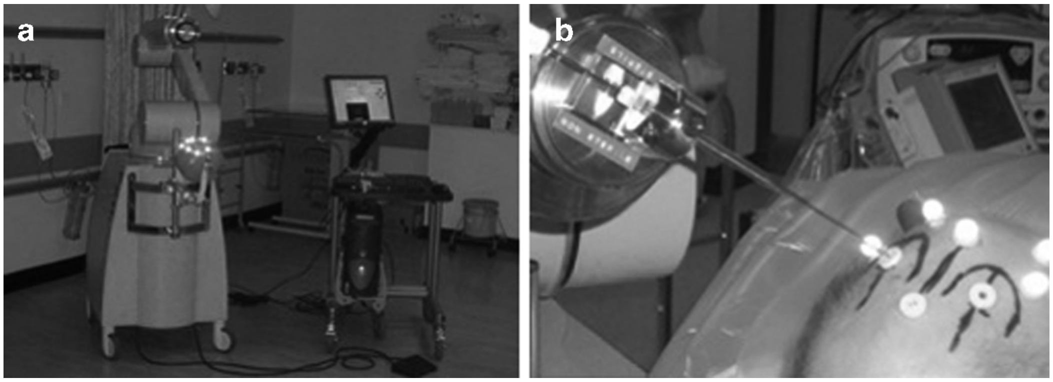


Fig. 30.2 (**a**, **b**) PathFinder and the instrument holder attachment inserting the electrode (adopted from Eljamel et al. [11])

Technologies, Caesarea, Israel) was used for these procedures. This is a miniature robot that mounts to the bony anatomy or to the patient's spine. After the mounting of the robot, pre-operative CT scan images are merged with intraoperative fluoroscopy images and registered to the operating field, with which the robot guides and assists the surgeon to execute a pre-planned procedure. Numerous cohort studies using this robot for minimally invasive spine surgeries have been reported with excellent results on safety and accuracy. Consensus of these experiments is that the robot is "helpful but not a *conditio sine qua non*" for performing these surgeries (Hardenbrook and Dominique et al. [14]). Controlled, head to head studies comparing the use of robots and freehand/fluoronavigation procedures by the surgeons, for efficacy and cost might help to clarify the relative benefit of a robot as compared to human operators. Having established its accuracy and safety, some design related modifications for better planning of surgical windows, graphical representation of virtual anatomy, and better connections of the end-effector to the bony anatomy are being advocated for further improvement of this system [14].

30.7 Robots for Microsurgery

Developing robotic devices for microsurgery is more challenging than for stereotactic procedures, as there are more functional parameters to be considered for design and construct of such a device. Microsurgical robots can be endoscopic robots, which can perform through a keyhole, or open microsurgical robots, which can operate by an open, larger incision and craniotomy.

The endoscopic tools for the brain have been useful for observing and performing minor operative actions like biting, penetrating, or dilating a hole with a balloon (for ventriculostomies). Angled rigid and flexible endoscopes especially help in observing around critical structures [15]. However, due to non-availability of working channels in a rigid endoscope and just one working channel in flexible endoscopes, much of any necessary surgical procedure might not be possible to be performed. NeuRobot, a telecontrolled micromanipulator system was developed to address these inadequacies [9]. This essentially consists of a manipulator with diameter of around a centimeter, which houses a 3D endoscope and three micromanipulators (each 1 mm in diameter) (see Fig. 30.3). This setup is mounted on a manipulator-supporting device, which has six degrees of freedom, and each micromanipulator has three degrees of freedom (up and down, rotational, flexion from 0 to 90°). Basic surgical procedures like dissecting, cutting, coagulating, stitching and tying sutures can all be performed by the surgeon, with visual feedback provided via 3D monitors. Haptic feedback is also provided to help with movement.

This device was used in cadaver experiments to perform surgery through endoscopic and a larger regular incision (pterional approach). This device is reportedly able to reach out to structures around a point to a limited extent.

Robot assisted surgical planning for tumor resection, craniotomy and reconstruction have been performed. The reconstruction of the bony part can be performed after the primary surgery for tumor resection by computer-aided design and planning of the implant size and shape that would be needed for a reconstructive surgery. This helps to avoid the time delay to design an implant and schedule a second cranioplasty, as is done currently in most cases [16].

NeuroArm is a comprehensive robotic system developed at the University of Calgary (Sutherland et al.) with intraoperative MRI ability and the ability to perform both image-guided procedures (stereotaxy) and motion scaled fine open micro-neurosurgery. This is a master slave robotic system, which consists of a robot, a controller, and a workstation or console. The robot's design is adaptable to the kind of procedure performed and based on surgeons' dual arm (ambidextrous) design. The robot has two arms, each with seven degrees of freedom and one degree of freedom for tool actuation, attached to each end effector (see Table 30.1). This, along with the intraoperative imaging, is considered a crucial design feat that can benefit in bringing dexterity and accuracy to the procedures performed. The tools attached to the arms can be either standard tools such as bipolar forceps, needle drivers and dissectors, or stereotactic instruments such as electrodes. The end effectors have a haptic feedback mechanism in place that helps in precise controlled movements by the operator.

Real time MRI is an important addition to NeuroArm over previous generation of robots. It helps in navigation of the tools with improved tool positioning and adequate tissue sampling during stereotaxy. For the microsurgery, MRI hasn't been clearly examined, nevertheless it is supposed that having constant intraoperative MRI would help monitor the position of the tool tips and help avoid a "no-entry" zone before and during the surgery, adding a safety mechanism [7].

The workstation is designed to provide an immersive environment for the surgeon. It has tactile, audio and visual feedback with binocular display providing three-dimensional vision of the operative site (see Table 30.2). Other than this there are desk-mounted displays of MRI, a robot operative parameters display and multidirectional surgical site views. The tools, attached to end effectors, can be superimposed on the MRI to provide navigation to the surgeon.

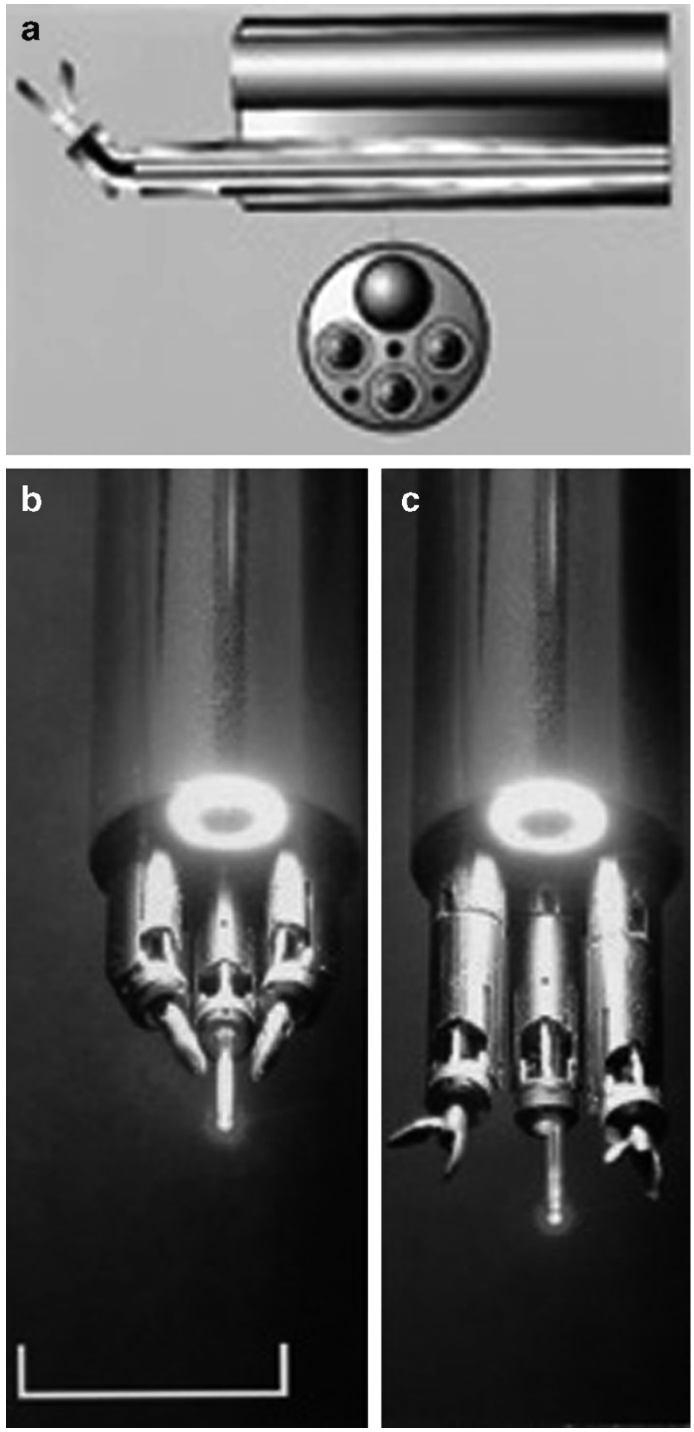


Fig. 30.3 (**a**, **b**, **c**) Design of the NeuRobot manipulator and associated instruments – endoscope, micromanipulators and a laser source (from Hongo et al. [9])

Other than performing surgery with NeuroArm, image processing and integration with the robot helps by providing simulations of surgery before the actual surgery. These virtual surgery trials could possibly help neurosurgeons practice,

Table 30.1 NeuroArm mechanical specifications

Parameters	Specification
Degrees of freedom	8 (including tool actuation) for each arm; 16 total
Payload	0.5 kg
Force (static)	10 N
Tool tip speed	Surgery: 0.5–50 mm/s Tool change: 200 mm/s
Positional accuracy	
Payload $< 100\ g$	± 1 mm absolute 100 μm resolution
Payload $> 100\ g$	± 2 mm absolute 1 mm resolution
Optical force sensors	Sensitivity: 0.02–5 N Dynamic range: 450:1
Continuous operation time	$>$ 10 h

Table 30.2 NeuroArm workstation specifications*

Parameters	Specification
Hand controller	6-DOF position sensing 3-DOF translational force feedback using direct current motors Workspace (tool tip) $x \times y \times z$ (ellipsoid) 40 × 25 × 50 cm Pitch, ± 130 degrees, × 150 degrees, roll, × 168 degrees
Microscope	Counterbalanced microscope equipped with motorized and high-quality optics Beam splitter with two high-resolution IVC camera High-definition format
Visual display	Binoculars using miniature display technology XGA resolution
Voice communication	Simultaneous talk/listen voice communication Wireless digital headset

*DOF, degrees of freedom, XGA, extended *graphic array*.

compare and analyze difficult techniques to arrive at an optimal solution for complex problems. By combining image processing with brain biophysical property modeling and with data on tool–tissue interactions, realistic projections of hemorrhage will help eliminate the gap between virtuality and reality.

Robots have also been used to enhance surgeon presence in neurocritical care units. With camera and video screen mounted on a remotely controlled mobile robot called the RP-6 (In Touch Health Inc, Santa Barbara, CA), the surgeon is able to be virtually present near the patient to observe and verbally respond [17].

30.8 Surgical Robotics Research at the University of Washington: Perspective of a Research Group

Raven is a surgical robot developed at the University of Washington. The main advantages of Raven is its relatively smaller size and design features for being operated remotely. The other advantage is a spherical design of the effectors that limits the range of motion at the surgical port location. This mechanical safety design is fail safe with respect to a software-based control in other robotic systems. This robot was initially developed for general surgical and urologic procedures. Later, it was adapted to perform suctioning in micro anastomotic procedures with a surgical suction tool attached to the end effector. It was used to experiment in micro anastomotic procedures in chicken wings. The Raven is a robot with master slave control system, with the movements of the surgical assistant on a console being downscaled and reproduced in the surgical field.

30.9 Roboscope in Neurosurgery: Minimal Access Curvilinear Surgery in the Brain

Currently minimal access surgery in neurosurgery is in its initial stages. A few endoscopic procedures like endoscopic ventriculostomies and transnasal transphenoidal procedures to the median anterior skull base have recently been introduced to mainstream neurosurgery, albeit with reservations. Minimal access surgery in its current form is performed with instruments that can work only along a straight line of access. The ability to work along a curved line will confer better surgical range and more applications for endoscopic procedures. Nevertheless, a whole new array of surgical tools will be required to operate along a curved access pathways. Robots in neurosurgery can aid in performing surgery through minimal access curvilinear approach similar to that being performed in Natural Orifice Transluminal Endoscopic Surgery (NOTES). Pre-operative planning, instrument navigation and advancement can all benefit with the superior geometric accuracy of a robotic device (Figs. 30.4 and 30.5).

Our team is pursuing the idea of minimal access neurosurgery with the design and development of a flexible robotic sheath called Roboscope (in collaboration with SPI Surgical, Seattle, WA, USA). This robotic device is a multi-jointed flexible tube with multiple degrees of freedom through which various operating instruments like dissectors, suction tubes, scopes, etc. pass through. The advantage of a flexible design is to take a curvilinear approach to the site of surgery, along the path of safe entry zones. This robotic device is computer guided, which helps direct through the required turns at specific anatomic points (Fig. 30.6). A CT or MRI guidance can be used for this purpose. Such image guided flexible robotic systems may provide endoscopic surgical options for conditions that are currently treated with open microsurgery.

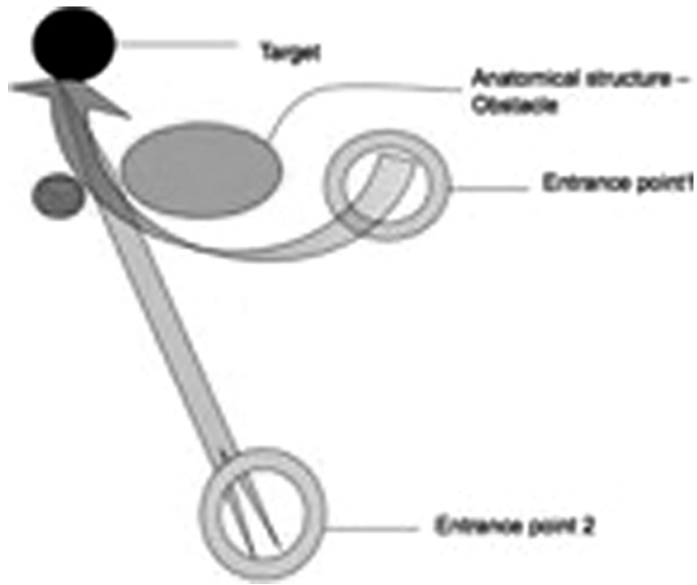


Fig. 30.4 This conceptual figure shows the need for a curvilinear pathway to negotiate obstacles when the entrance site must be in one area (entrance point 1) vs another (entrance point 2)

This device can be compositely used with other technologies being developed for minimal access surgery. Nanotechnology based tumor treatments, cryoablation, and high frequency ultrasound for tumors can all be performed though this device.

30.10 Design of Roboscope's Main Flexible Access Port System

The access port system is a flexible construct, with multi jointed links connected in a serial fashion. This serves the purpose of a **maneuverable** channel though which surgical instruments can pass to the site of surgery. The jointed links are connected and mechanically operated through cables or wires running along the circumference, at certain points in association with wheels (pulley wheel mechanism). Depending on the design of two cables or four cables, the device can bend in one plane or have biplanar bending ability (Fig. 30.6). This movement is controlled through the external robotic device. The movement of the cables provides up to two degrees of freedom for the movement of the robotic scope (Fig. 30.6). The cables at the instrument end however, have articulations with a sphere, which provides additional rotational degrees of freedom along with axial movement (Fig. 30.7). Depending on the nature of the design employed at the end articulation of instrument, it can have different degrees of freedom and movement at the working end (Figs. 30.9–30.12).

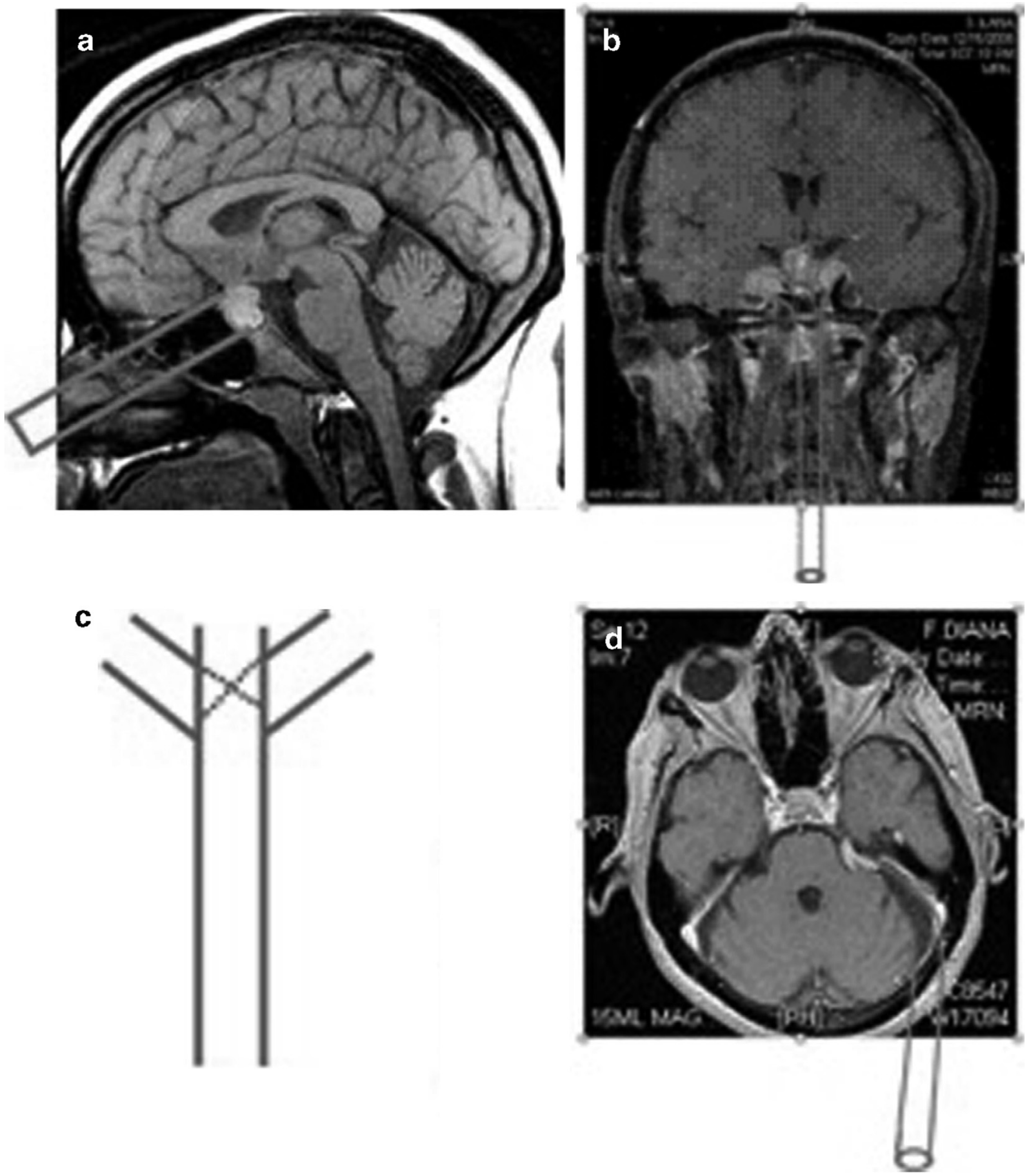
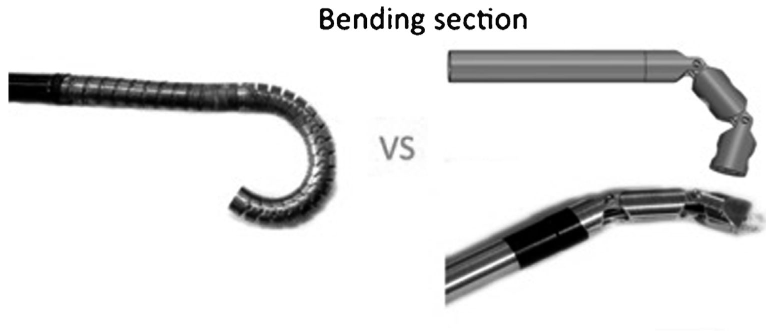


Fig. 30.5 (**a**, **b** and **c**) MRI image showing a pituitary tumor extending laterally that cannot be operated via a transnasal endoscopic approach. A curvilinear approach with the Roboscope would make such an approach possible. (**d**) Posterior fossa meningioma which can be approached and removed by a standard retrosigmoid craniotomy. In order to access and remove this tumor, however, a minimal access approach through the retrosigmoid area will require curvilinear instrumentation. This is a case for performing an endoscopic surgery where open microsurgery would normally be done

For the advancement of Roboscope through the brain, the Roboscope at the functional end has two movable curved plaves which oppose each other to form a pointed surface. The pointed surface can help pierce through planes, by separating tissues on either side, thereby making a plane for advancement of robotic scope in a planned trajectory.



2 cables	2 way articulation (Left/Right)
4 cables	4 way spatial / 2 way planar "S" shape

Fig. 30.6 Illustrating the bendable design of the roboscope

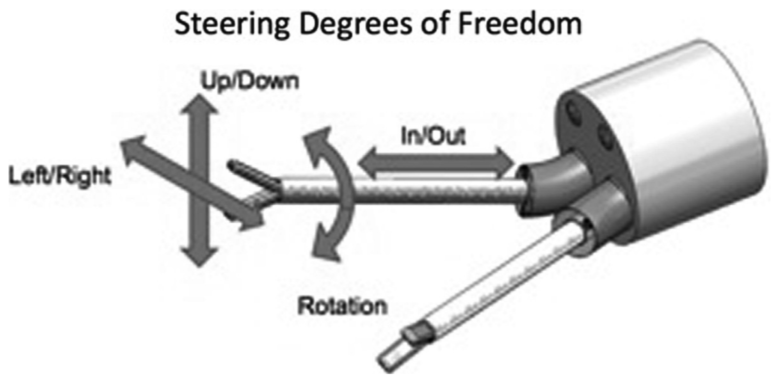
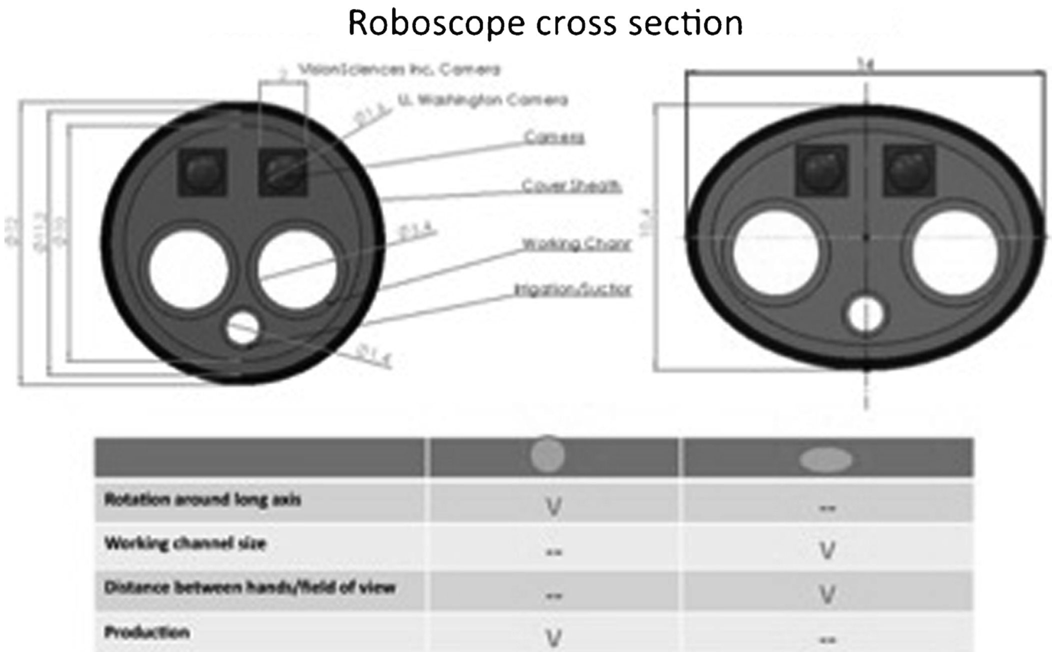


Fig. 30.7 Illustration showing the degrees of freedom needed at the end of operating tools

30.11 Instruments Passing Through the Roboscope

This robotic port system will house atleast two working channels through which surgical instruments can pass, including a modified bipolar instrument (Fig. 30.8). The flexible scope can have a cross section of a circle or oval design. The instruments inside the Roboscope are actually held in a sheath, which can be either fixed or freely movable within the scope. The sheaths, depending on the design, have an axial or rotational movement capability (Figs. 30.9–30.12). The scope also houses two camera heads providing for binocular vision. A suction device is located radially, which could also be maneuvered directionally. This device also has the ability to spray clean the endoscopic camera heads. A flexible CO_2 laser tube can also be used through this port, which holds the suction device.

The two working channels used in the robotic device will be designed to accommodate cryoablation or thermo ablation devices, or future nanotechnology instruments helping in advanced imaging or drug delivery.



Rotation around long axis	V	--
Working channel size	--	V
Distance between hands/field of view	--	V
Production	V	--

Fig. 30.8 Cross section of the Roboscope showing the arrangement of ports for intruments and the degrees of freedom. Description of degrees of freedom: (1) Cable up/down, (2) Cable left/right, (3) Tool in/out, and (4) Tools/rotation

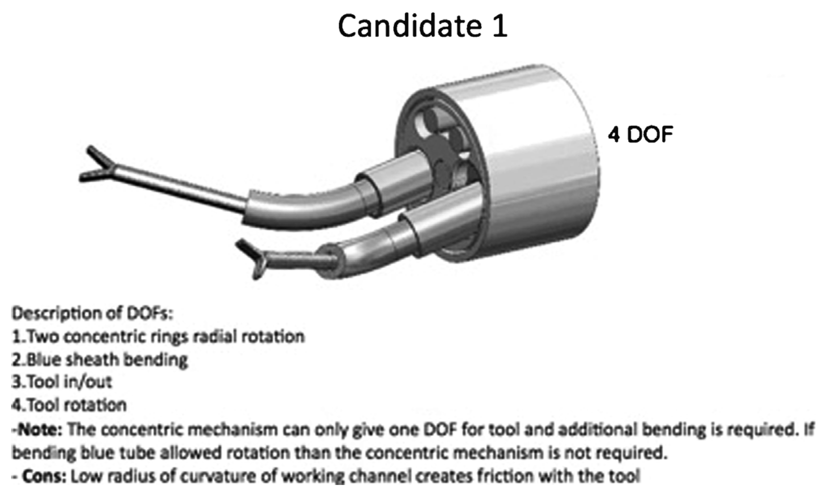


Fig. 30.9 Illustration showing the possible movements and degrees of freedom of the end operating instruments

30.12 Future of Robotics in Neurosurgery

The future of robotics in neurosurgery will be based on the need for precision in smaller operative spaces.

Robotic master slave robots take more time than a standard microsurgical operation performed by a surgeon. This may limit the use of robots in long surgical

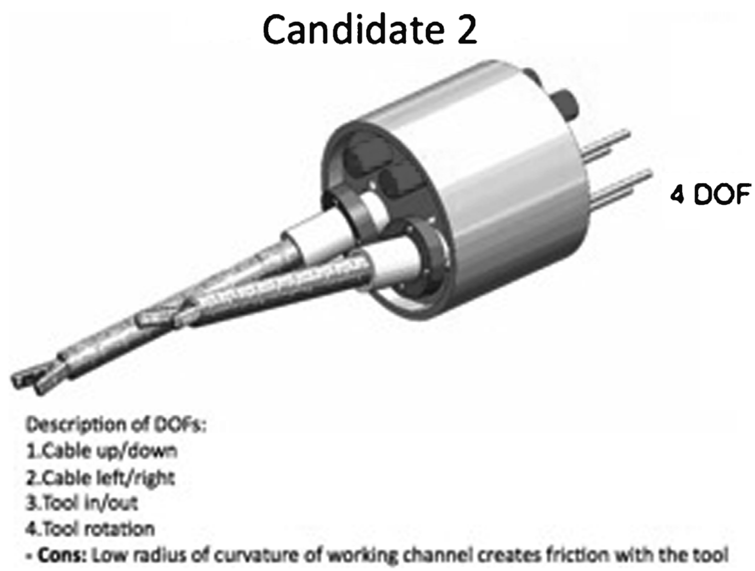


Fig. 30.10 Alternative design, with narrower field of access and radius of curvature

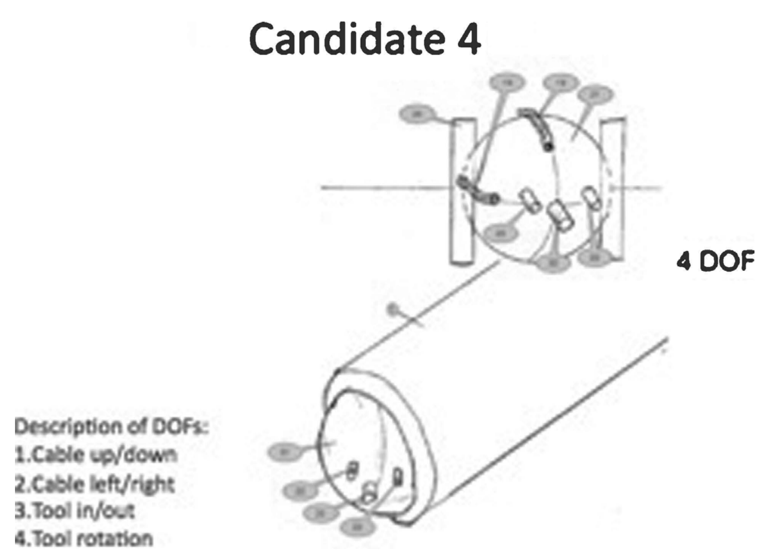


Fig. 30.11 Mechanism of " wire and sphere" movements and description of the degrees of freedom

procedures. However, the operative time while using a robot can be decreased with operator training and design optimization of the robot (as experienced in many of our robotic experiments).

Incorporation of various preoperative images such as functional MRI, diffusion tensor imaging, three dimensional angiography, and intelligent solutions to help get the surgeon to the target site without the destruction of normal tissues will be key reasons for using robotic devices. Smaller sized robotic machines (possibly micro or nano) may help to create robots which can self assemble, and disassemble after performing the required task. Such robots can find a place in endovascular surgery, intraventricular surgery, and tumor surgery through a small space.

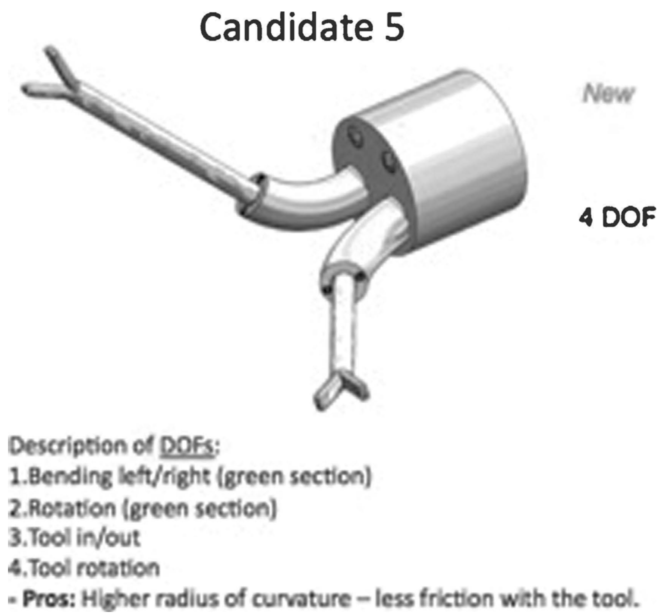


Fig. 30.12 This figure illustrates the wide range of movement of the surgical devices at the end which can be useful in dissecting larger tumors/lesions without much movement of the robotic scope. Most of the range of movement is conferred by the flexibility of the sheath that houses the surgical instrument

Robots such as NeuroArm, despite being commercially available for more than a year now, are not widely used in operative microsurgery. A system that confers on us the ability to perform surgeries that can otherwise not be done with existing technology will be readily tested and adopted. Curvilinear, minimal access surgery is one such technology, which can help neurosurgeons reach beyond the current frontiers.

30.13 Teamwork

Creation of medical robots require a multidisciplinary team with close collaboration between surgeons and engineers. The research group at the University of Calgary that developed NeuroArm may be a good example of a successful team effort. Our research group at the University of Washington, working on Robo scope is based on similar lines with collaborative effort involving surgeons, engineers and business associates from industry. A typical team would consist of lead surgeons with expertise in surgical specialties such as neurosurgery and ENT detailing the requirements of a proposed device to a team of engineers and business associates. The team of engineers involves professors and graduate students in electrical and mechanical engineering and nanotechnology to translate the surgical requirements into a manufacturable design. Business representatives help with financial plans and timelines for these processes.

30.14 Discussions

Despite the advances in the use of robots in neurosurgery, there are some downsides, some of which might be generalized to all surgical specialties. Robots, like any other machine, would have the risk of technical failure. As seen with few examples, initial stages of their development and use would have more of such risk and failures, which may be corrected in course of time as with any new complex technological application [3,18].

The issue of safety will be the primary concern that any new device needs to address first. There are numerous mechanisms developed in robotics which prevent the robot from a lock down, such as dual mechanisms or feedback loops for critical steps. These would help avoid unexpected errors that could be potentially harmful. Such safety features are also a necessity to help meet the standards of complex regulations in place for medical device industry.

Secondly, robots, being bulky by design, could occupy a lot of operative space, making it difficult for surgeons to operate with them. This is especially true in neurosurgery with smaller operative exposures and deep location of actual field of surgery. The issue of sterilization before use also needs to addressed in the design of the robot.

Finally, the quality of work performed with robots needs to be superior or at least equal to that of good surgeons, within reasonably similar cost brackets. Fulfilling this criterion would be an absolute necessity for a robot to be embraced by the surgeons. Currently, open micro-neurosurgery as performed by experienced neurosurgeons meets or exceeds the expected standards for the procedure. Use of a robot to substitute surgeons in this situation might be not be essential in performing or improving the surgery, though it might help make performing the procedure easier for the surgeon. Such redundancy can be an important determinant in wide acceptance or usage of robots among surgeons. The da Vinci is a good example of this [1]. Though initially designed for performing cardiac bypass surgeries, it is not being used for its intended purpose, as cardiac surgeons are able to perform the procedures equally well or better without the robot. However, it has found its place in bettering prostatic and gynecologic surgeries, where surgeons were not traditionally microsurgery trained. On this note, a definite case where robots can help neurosurgeons by providing valuable tools is curvilinear endoscopic surgery. Such surgeries are beyond the scope of neurosurgery in its current form.

After the stage of the acceptance of robotic surgery as a standard of care, the overall benefit to the population would largely depend on adequate training of surgeons and complication avoidance. This brings the need to have a quantitative evaluation system for assessing surgical skills in utilizing such technology, as with several studies now being performed for the evaluation of minimally invasive surgery techniques in general surgery [19].

One of the other major hurdles for such ambitious ventures is in getting research funding [10]. The road from design and manufacture of the robot in the lab to the operating room is a very long and tedious one. It is a difficult task to sustain the economic means to pursue such endeavors, more so with the ongoing debate and downsizing of federal health spending. Increasing government control of the health care in many countries can impose limitations on the development and adoption of new medical technology, especially in the neurosurgical market as it is smaller campared to other specialties.

30.15 Conclusion

For robots to be embraced in neurosurgery, it would need a fine complement of human strengths such as judgment and ability to react to situations, with the advantages of the robot. Reaching this fine balance is a function of advancing technology and appropriate design. Design of robots that can contribute accuracy, indefatigability and zero tremor to a surgeon's judgement could possibly help push the limits of human performance in microsurgery. Neurosurgery in the future, especially with the minimal access techniques, requiring superlative technical and fine motor skills would benefit from such a system. Much remains to be seen whether the heights of engineering can appropriately complement the finesse of the fingers, which has evolved over millions of years.

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