Chapter 19
Robotics in Neurosurgical Training

Michael Y. Bai, Hussam Abou-Al-Shaar, Zachary C. Gersey, Daryl P. Fields, and Nitin Agarwal

Introduction

A surgical robot is a powered computer controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks [1].The Czech novelist and playwright, Karel Čapek, first coined the word robot to describe automated machines in his science-fiction play, "R.U.R—Rossumovi Univerzální Roboti" in 1921, originating from the Czech word robota for forced labor [2]. The first industrial applications of robotics can be traced back to the partnership forged between George Devol and Joseph Engelberger. In 1959, General Motors installed the fruits of their labor, the Unimate #001 (which Devol termed a "Programmed Article Transfer Device") at its die casting production line in New Jersey, ushering in a new era of manufacturing. It was not until 25 years later when robotic technology was first used in the operating theater. An industrial robotic arm, the PUMA 200 (Programmable Universal Machine for Assembly), was used to perform a stereotactic brain biopsy with 0.05 mm accuracy. This system was the prototype for the dawn of robotic-assisted neurosurgery.

Since then, technological advances continue to the present day with several integrated systems allowing improved precision, high accuracy, and decreased complications, and thereby increasing the capabilities of the surgeon in minimally invasive surgical procedures. As a result, the use of diverse robotic devices has rapidly expanded into the medical and surgical arena to completely revolutionize the provision of care. Robots are perceived to relieve some amount of labor from surgeons, but robotic surgery still requires a considerable amount of skill and training to

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M. Y. Bai · H. Abou-Al-Shaar · Z. C. Gersey · D. P. Fields · N. Agarwal (✉)
Department of Neurological Surgery and Epilepsy Center, University of Pittsburgh
Medical Center, Pittsburgh, PA, USA
e-mail: aboualshaarh@upmc.edu; gerseyzc@upmc.edu; fieldsdp@upmc.edu; agarwaln@upmc.edu

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perform on the part of the operator. Today, robotics mainly support the desire for minimally invasive, stereotactic surgery with robots being physical extensions of computer systems that interact with surgeons to provide improved accuracy in surgical site location, reduced invasiveness, increased precision of surgical tool motion, and overall better surgical outcomes. Since the first use of surgical robots in 1985, the field has exploded and represents a new paradigm shift in medicine and surgery. While the use of robotics in neurosurgery is still in its early stages, its use has become widespread in laparoscopy, gynecology, vascular surgery, cardiothoracic surgery, urology, and respiratory interventions [3].

Neurorobotics is accelerating at a rapid pace. Technological and economic advances will allow robots to become smaller, stronger, faster, and more precise than ever before. Their ability to perform complex tasks with great accuracy and reliability is what makes robots ideal for neurosurgery. Robots can also enhance the visual and manual dexterity of surgeons and allow them to see and reach areas of the brain that were previously inaccessible. It can also allow for unconventional approaches to access areas of the brain that would previously have been considered “too risky” or “inoperable” and therefore reduce harm to patients, increase the chances of surgical success, and improve postoperative recovery and quality of life. In many academic centers, robotic surgery became part of the training for residents and fellows (Fig. 19.1), which had been incorporated into the academic curriculum.

Fig. 19.1 Intraoperative image depicting active resident participation in robotic-assisted surgery for a patient with medically refractory epilepsy undergoing SEEG. The robot is utilized during various parts of the procedure including preoperative planning (**a**), registration (**b**), SEEG drilling (**c**), and SEEG lead implantation (**d**)

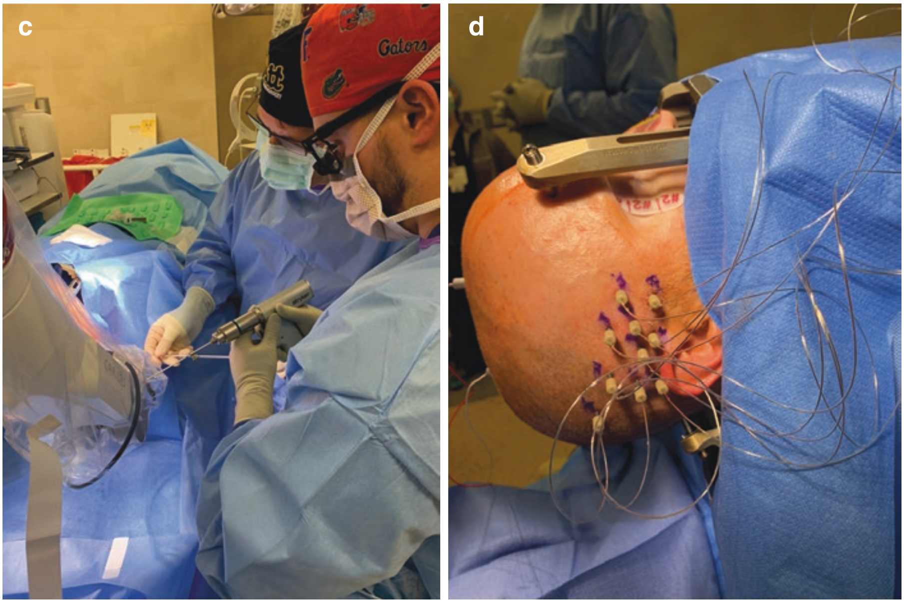

Fig. 19.1 (continued)

We anticipate that robotic surgery competency will become a necessary step for a complete neurosurgical training as imaging guiding surgery, as an example. This chapter provides an overview of robotics utilization in neurosurgical procedures and training of residents and fellows, spanning from their origin, current perspective, and future implications.

Historical Perspective

The first robotic surgery systems were designed for brain tumor biopsies [4]. In April 1985, Dr. Yik San Kwoh used the Unimation PUMA (Programmable Universal Machine for Assembly) 200 robot, which was a machine designed for industrial use, to position a needle precisely using computed tomography (CT) guidance in a 52-year-old male when performing a stereotactic biopsy of a deep intracerebral lesion [4]. The ability of the robot to calculate its movements based on the stereotactic frame resulted in delivery of faster and more accurate results than any other method available at the time. Kwoh et al. demonstrated that robots assistance could be safely employed along with the use of a stereotactic frame during neurosurgical procedures [5]. This development was soon followed by the use of the same robot (PUMA 200) as an assistant to retract delicate neural structures during the surgical resection of low-grade thalamic tumors in children [6]. However, the PUMA 200 robot was limited in neurosurgical applications and was eventually surpassed in capabilities by the MINERVA (University of Lausanne, Switzerland) robot in 1995, which allowed the use of real-time CT to guide stereotactic biopsy probes [5].

The concept of robotics progressed further, and technological advancements led to a multitude of diverse robotic devices such as the ROSA, which gained FDA approval in 2012 [7] (Robotic Stereotactic Assistance—Medtech, Montpellier, France) NeuroArm (2007 launch, technology acquired in 2010 by IMRIS, Minnetonka, MN) [8], NeuroBlate (2013 release, Monteris Medical. Plymouth MN) [9], Pathfinder (consortium) [10], Renaissance (technology acquired by Medtronic 2018, Minneapolis, MN), and Neuromate (Renishaw plc, Wotton-under-Edge, UK) [11].

Robotic Types

The differences in the function and application of a robot as well as the type of robot–surgeon interaction is key to describing different types of surgical robots [12]. The three basic categories of surgical robots are:

- Dependent: the surgeon controls every movement of the robot such as with the da Vinci Surgical System.
- Autonomous: the robot can perform pre-programmed actions with close supervision of the surgeon.
- Shared control: both the surgeon and robot control actions concurrently.

Dependent Systems

Dependent systems are the most popular type of robots as the surgeon retains full control over the actions of the robot. Also known as master-slave systems, these robots enhance the capabilities of the human surgeon by allowing the surgeon greater comfort, precision, visualization, and ability to operate remotely while simultaneously reducing the size of the surgical field, operative time, and complications [12].

Autonomous Systems

The robots assist the surgeon to carry out precise tasks. They are pre-programmed to perform a specific motion or move tools to set locations. The success of this type of system is dependent on the technology itself, and complications can arise if the system has not been programmed correctly. As a result, a great deal of trust is associated when using these systems [12].

Robots like the Minerva (University of Lausanne, Lausanne, Switzerland) [5] and Pathfinder (consortium) [10] perform stereotactic tasks with or without a frame and have progressed from guiding biopsy needles and depth electrodes in the brain to planning and inserting pedicle screws in the spine. Supervised robots like the SpineAssist [13] and Renaissance [14] (both systems acquired by Medtronics, Minneapolis, MN) systems are now widely utilized in spinal instrumentation, and more recently have been approved for use in intracranial procedures [7, 15].

Shared Control Systems

Shared control systems are a combination of autonomous and dependent systems and involve the surgeon and the robot jointly controlling the instruments used to manipulate and dissect neural structures [12]. In this way, the precise actions of the robot can be combined with the manipulative skills and manual dexterity of the neurosurgeon. The instrument is held by the surgeon and the robot, allowing for finer dissection and elimination of tremor and muscle fatigue.

Utilization of Robotics in Neurosurgery

Robots have various applications in neurosurgery, including functional, spine, tumor, endovascular, and epilepsy surgery. Functional neurosurgery, in particular, witnessed a great deal of robotics integration and advancements throughout the years. The use of frameless robots in deep brain stimulation (DBS) and stereo electroencephalography (SEEG) is of particular interest [16, 17]. Examples of these in the field of deep brain stimulation include the work of Candela et al. [18] who used the Neuromate stereotactic robot (Renishaw plc, Wotton-under-Edge, UK) to assess the accuracy and safety of this device when used for electrode placement bilaterally in the globus pallidus internus (GPi) for deep brain stimulation in six pediatric patients suffering from hyperkinetic movement disorders. Primary outcome measurements were a comparison of actual electrode position placement determined by CT imaging compared with the preoperative planned coordinates, and through comparison of validated scales of dystonia and myoclonus acquired 1 month preoperatively and 6 months postoperatively. They concluded that the robot was both an accurate and safe tool for use in the placement of GPi electrodes. Neudorfer et al. [19] conducted a retrospective study comparing the accuracy, precision, reliability, duration of surgery, intraoperative imaging quality, safety, and maintenance between robot-assisted (ROSA Brain, MedTech, Montpellier, France) and conventional DBS surgical procedures. Their analysis of the outcomes of 80 patients led to the conclusion that robot-assisted DBS procedures were superior in terms of accuracy, precision, and operation time when compared to conventional DBS surgeries. Shorter procedure times were also observed to be a benefit of robot-assisted DBS surgeries by Vansickle et al. [20] in their study on 128 Parkinson's disease patients. Using the Renaissance robot (Medtronics, Minneapolis, MN), they aimed to demonstrate the effectiveness of DBS surgeries with asleep patients and fusion of preoperative magnetic resonance imaging (MRI) scans with intraoperative CT scans. Not only did they observe shorter operation times to the benefit of the patient, but also electrode placement was found to be accurate.

Another field in robot-assisted neurosurgery that has blossomed is in SEEG, in particular for epilepsy patients. In an earlier study [21] that evaluated SEEG safety and accuracy, using conventional and the ROSA robotic system (MedTech, Montpellier, France) for electrode placement, the authors found that use of the robotic device was equally successful at mapping the epileptogenic zone as use of conventional procedures. This result was also confirmed in two separate studies also employing the ROSA device with adult [22] and pediatric [23] patients. Almost simultaneous to these reports, a review of neurosurgical treatments of pediatric epilepsy also underscored the value of robotic assistance in SEEG as well as in laser interstitial thermal therapy [24]. Gonzalez-Martinez's group has since moved forward to investigate the validity of using the ROSA robot-assistive device for placement of electrodes for the Responsive Neurostimulator System (RNS, NeuroPace Inc., Mountainview, California) compared to frame-based or frameless stereotactic systems [25]. Their conclusion was again similar, pointing to the usefulness of robotic-assistive devices in neurosurgery: that robotic-assisted stereotaxis can be used to provide an accurate and safe method for implantation of RNS electrodes. Debenedictis et al. [26] have documented their extensive experience of the use of the ROSA robot-assisted device in 128 pediatric neurosurgical procedures (SEEG, neuroendoscopy, stereotactic biopsy, pallidotomy, shunt placement, deep brain stimulation procedures, and stereotactic cyst aspiration). Their results touted the versatility of the ROSA device for many different neurosurgical applications while maintaining safety and minimizing operative times. The future of robot-assisted neurosurgeries is bright and will be highlighted by further applications and technological advances including those in curvilinear needle guiding and brain imaging technologies [27].

Robotics also have applications in pain-related surgeries and treatments of psychiatric diseases such as depression and obsessive-compulsive disorder. MRI-guided robots are used in biopsies and telesurgery, as well as endoscopic endonasal trans-sphenoidal surgery for pituitary tumors and skull base lesions. Recently, the use of robotics in spinal surgery has gained an interest among neurosurgeons [28].

Another area in which robotics plays a role is in the development of the exoscope for surgical site visualization. Several different systems are available, each with their own advantages and limitations and choice will depend upon the type of surgery involved. However, they are all associated with much improved ergonomics in the operating theater when it comes to surgical site visualization and are also valuable for training and educational purposes [29–31]. Description of these systems is beyond the scope of this chapter.

Benefits and Limitations of Robotics in Neurosurgery

The benefits of robotic integration in neurosurgical procedures are numerous, which include increased dexterity for surgeons, minimally invasive access without loss of surgical ability, motion scaling (conversion of large movements to short movements of hands during surgery), and easier manipulation of small delicate structures. Neurosurgical robots have an advantage of integration with image guidance systems yielding increased precision, consistency, and accuracy minimizing the risk of iatrogenic injury to critical neurovascular structures. For example, in the placement of electrodes for DBS, robots allow for the precise alignment of multiple trajectories and ensure accurate placement of the leads in the desired location [32, 33]. An important aspect of neurosurgical robots is that they help to improve patient's comfort, shorten surgical procedure time, and reduce surgeon's fatigue during microscopic surgery [7, 34].

Robotic systems, however, are not without their own set of inherent limitations, which are predominantly related to elements of robotic systems (the technology) and aspects of training of surgeons regarding their application and use. Other concerns include the cost/benefit ratio, which could offset observed benefits and integration difficulties due to the bulky size of robotic systems. As with other forms of technology where the drive is for smaller and better, this should become less of a problem in the near future. Latency in movement, lack of tactile feedback, and risks of mechanical failure and malfunction are other apprehensions of robotics use in surgery [1, 12, 33, 35].

Augmented Reality

Augmented reality (AR) or virtual reality (VR) refers to the ability to overlay artificial images or other useful information onto the operative visual field [12]. This would enable surgeons to incorporate patient specific preoperative images obtained from CT, MRI, or X-ray into their live view of the patient and therefore enhance their awareness of important unperceived structures within the patient's anatomy and plan surgical procedures.

Technologies such as the Google Glasses (Google Inc., Mountain View, CA), HoloLens (Microsoft Inc., Redmond, WA) allow 3D reconstruction of useful images in front of the surgical field [36, 37]. They can display information such as tumor location, pedicle screw trajectories, and nearby important neurovascular structures.

AR can be combined with surgical robotics to achieve an integrated system comprising of a slave system performing the surgery, a master system controlling the slave system, an imaging system with live images of the operating field, and an AR display attaching markers to the images [38]. Such combined robotic and AR surgery has been reported in laparoscopic procedures, including nephrectomies and liver segmentectomies [39–41].

In the future, AR visualization may be taken from the robot's point of view, with surgeons controlling the system from outside of the sterile field. With advances in live, intraoperative imaging, this technology has the capability of completely revolutionizing neurosurgery with enhanced accuracy and reduced complications. In fact, in a recent review, it was determined that AR is constantly improving the effectiveness of training physicians and the overall outcomes of the treatment [42]. AR can be combined with other technologies that give surgeons greater control, such as intuitive, responsive controls with sensitive haptic feedback. This will allow surgeons to become fully immersed in AR while protecting the patient from the limitations of a human operator (such as fatigue, muscle tremor, and orientation).

Neurosurgical Training

The first surgical training program, established by William Stewart Halsted at Johns Hopkins, set the foundation for modern surgical residency programs [43]. His program comprised the basic sciences, research, and graduated responsibility of patients in the operating room, now supplemented by the observation of experts, practice on cadavers, and VR platforms. The latter has been developed and grown in a manner analogous to avionic flight simulators [44] for a variety of procedures, including simulations of ventriculostomies, pedicle screw placement, image-guided microsurgical procedures, planning of stereotactic radiosurgery, and remote surgical assistance of cadaveric surgery. Amongst the first of these VR platforms designed specifically for neurosurgery was described by Kockro et al. [45] They developed the VIVIAN (Virtual Intracranial Visualization and Navigation) system for the Dextroscope (Bracco, Milan, Italy), a virtual reality environment, which has since proven valuable in several neurosurgical training scenarios [46–48]. However, it lacked haptic feedback. Malone et al. [49] have reviewed some of the earlier developments in neurosurgical simulations. In 2012, Delorme et al. [50] outlined their efforts at designing a VR platform that incorporated haptic feedback (Neurotouch/NeuroVR, Saint-Laurent, Québec, Canada), which consisted of a stereovision system, bimanual haptic tool manipulators, and a powerful (at that time) computer and set up for beta testing at 7 teaching hospitals in Canada. A more complete training framework surrounding the Neurotouch was then established [51]. The framework consisted of five modules deemed representative of basic and advanced neurosurgical skill. These were ventriculostomy, endoscopic nasal navigation, tumor debulking, hemostasis, and microdissection. Further improvements of the Neurotouch system were later developed for the extraction of data which was used for further evaluation and metrics of trainee performance [52]. This simulator was later used to show through force pyramid analysis that certain tumor regions required greater psychomotor ability to resect. This knowledge could then be used as a focus for further resident training efforts [53, 54], with expertise in technique now being evaluated with the assistance of artificial intelligence and machine learning algorithms [55, 56]. The technology has now advanced to the point where it can evaluate and quantify neurosurgeon tremor [57].Other simulators continue to be developed to address the important issue of surgeon training, for example, a recent system that combines real brain tissue with 3D printing and augmented reality [58].Another example is a method of training fine-motor skills such as Microscopic Selection Task (MST) using virtual reality (VR) with objective quantification of performance and introduction of vibrotactile feedback (VTFB) to study its impact on training performance. The results were promising, as MST with VTFB led to faster completion of MST with higher precision and accuracy compared to that without VTFB [59].

Though these advances in virtual reality for surgical technique and evaluation are helpful training aids, the training of surgeons in robotics remains a challenging issue. It is time consuming, placing emphasis on proficiency, dexterity, robotics knowledge, and skills acquisition. It involves learning the basic kinematics of using machines and their control systems, which can involve AR and VR platforms and/or cadavers. Surgeons are trained to improve their technical, clinical, and cognitive abilities and skills to assist their adoption of these new technologies [41, 60–62]. Thus, with the application of robot-assisted surgery, there is an increased need for training, and while the traditional methods have been effective, more modern methods such as dual robotic consoles and AR and VR platforms show great promise, but not yet widely adopted [63].

Training programs should aim to integrate theory and training across simulated and cadaveric domains. The first step in robotics training of surgeons starts with theoretical training followed by simulation. Inanimate simulation exercises are characterized by good construct validity and have been employed in criterion-based training [64]. Simulation has gained acclaim over the last two decades [65–67], and a plethora of simulation platforms and software are available today from companies such as Mimic Technologies (Seattle WA), Simulab (Seattle WA), Insimo (Strasbourg, France), FundamentalVR (London UK), among others.

Examples of these training programs include VR surgery training that can utilize pre-designed scenarios to allow trainees to practice particular skills. Both AR and VR have been associated with greater improvement of skills and provide the advantage of remote robotically assisted surgeries [68]. They can also be designed around a patient's specific anatomy involving rare and challenging cases and to allow preoperative preparation in a personalized approach to treatment [12, 69]. The advantage of VR training is that surgeons are able to receive tuned haptic feedback, which is often cited as an important feature of surgical robots [1, 12, 70]. Haptic feedback in robotic surgery is especially important, and is believed to reduce operative time and surgical errors. In a recent study, the importance of adding a superior haptic feedback device in telerobotic surgery for standardization of surgery and care was evaluated. The conclusion clearly showed that the choice of haptic hand controller was very significant in the outcomes [71]. Indeed, results indicate that haptic feedback in VR training is especially important during early phase acquisition of psychomotor skills [69]. Applications of VR include case planning, playback, and rehearsal, which will become especially beneficial for neurosurgical training. Incorporation of VR simulators in surgical curricula is of great interest for robot-assisted training. Many VR simulators exist, but the most prominent include the dV trainer (Mimic Technologies, Seattle WA; mimicsimulation.com), the robotic surgical simulator “RoSS” system (Simulated Surgical Systems, San Jose CA), RobotiX mentor (3D Systems, Littleton CO), and the da Vinci skills stimulator (Intuitive Surgical Inc., Sunnyvale CA) [72].

The da Vinci system (Intuitive Surgical, Inc., Sunnyvale, CA) is the most widely used surgical robot approved by the FDA for various operations. In just 9 years since its introduction to the market, the da Vinci system is now used in 80% of radical prostatectomies conducted in the US. The system also provides a platform for trainees to develop expertise in robotic skills. In addition, this system has shown good construct validity of an in vivo exercise testing which discriminates novice and expert surgeon competencies, hence supporting evidence of benefit associated with VR exercises [73]. The da Vinci Research Kit (dVRK) has been instrumental in development of novel software frameworks to prototype and test gradations of human–robot interactions and automation in surgical robots according to trainees’ performance levels [74]. In fact, the framework developed by Enayati et al. [75] highlighted the potential of robotic assistance in visuomotor training though further research is needed to validate generalizability of their findings.

Although the da Vinci surgical system offers seven degrees of freedom in range of motion (equivalent to the human arm) and is considered to be the most widely used robotic system in the world [2], its adoption into neurosurgery has been hindered due to the limited tools available, the number of ports needed, and size of the machinery. The steady hand system is the only version reported to be in use in micro-neurosurgery [12].

Perhaps superior to the completely robotic and digital approaches described above, robotic systems training through cadaveric surgeries allows utility of proprioceptive feedback. Trainees can improve their technique by conducting experiments on human cadavers. For this reason, the coordination of cadaveric use to increase the availability of human training sites is recommended [35]. Though considerably more expensive, it is still considered the best way to practice because it gives a better representation of the surgical field [12]. Cadaveric training is, however, limited by single time use and leading some to conclude that inanimate training including VR exercises is most effective in standardized curricula [76].

Robot-Assisted Surgical Training

Advantages

Computer simulations paired with robotics such as in the previously mentioned RobotiX mentor (3D Systems, Littleton CO) and the da Vinci skills stimulator (Intuitive Surgical Inc., Sunnyvale CA; intuitive.com) systems produce high quality programs for trainee surgeons to equip them with dexterity, precision, and speed so that they can work efficiently whilst ensuring patients’ safety [77]. Neurosurgical training makes use of surgical based simulations, which exhibit high performance and are cost efficient [78]. Robotic surgical systems also provide better 3D visualization of surgery, with increasing capability for sensory immersion [35, 79].

Limitations

Similar to robotic utilization in surgical procedures, there are several limitations for using robots in surgery training. Surgical robotic systems are expensive, with hefty prices involved in the maintenance of a robot and the use of instruments [78]. In robot-assisted surgery, the robots and instruments must be changed every 8–10 operations [78, 79]. Furthermore, the Da Vinci Surgical System is the most modern and most developed system for surgery, but requires large operating rooms [79]. 3D spatial navigation and visual spatial coordination have in the past been cited as two additional limitations in robotic neurosurgery [80], as for the machine to think in a complex 3D environment is computationally demanding and limited by sensor technology.

Prerequisites

Although robotically assisted surgeries have spiked worldwide in the last two decades, there is no standardized training or unified credentialing system in place. As the demand for this technology grows, it is imperative to devise a formal comprehensive robotic neurosurgical training program and validated assessment tool to achieve safe practices and best patient outcomes with the greater goal to prepare trainees for independent practice. Combined simulation-based training and didactic lessons support training through progressive skills acquisition [81].

As prerequisites, trainees should have knowledge about robot-assisted surgery, its parameters, and its functions. Information about surgical procedures should also be known. Surgical procedures involving robots include how to select patients for surgery, what to do in the event of complications, and the appropriate distance between the robotic system and patient [77]. Secondly, training for robotic neurosurgery should be performed as much as possible in the laboratory using robotic simulator systems; using operating theater robotic systems extensively for training is not cost effective [77, 82]. Thirdly, trainees should be familiar with VR training, which has a vital role in learning to use robots in robot-assisted neurosurgery [77]. Lastly, a trainee should be aware of how to use human and animal cadavers for robotics training. Animal simulation models can be used but due to ethical concerns their use is limited [83].

Mentoring, proctoring, and precepting are valuable throughout the training period and beyond. Institutions should provide necessary resources needed for supporting these experiences. Training should proceed from surgical observation and assistance to autonomous performance of surgical tasks. Therefore, active trainee involvement during procedures has to be addressed either through surgeon shifts during procedure or employing surgical robotic systems. In a survey of residents regarding their attitude and compliance towards robotic surgery training, the authors identified that the non-mandatory structured robotic training curriculum used at their institution was insufficient in helping them gain fundamental robotic skills. Specific problems identified were the amount of time they needed to invest in the program and lack of access to a simulator [84].

The scarcity of assessment tools and methods specifically employed in neurosurgical robotics training is strikingly evident. The Global Evaluative Assessment of Robotic Skills (GEARS) [85] is a validated tool to differentiate expertise in robotic surgery which can be integrated with metrics available in robotic surgery simulators. Other assessment tools in use include the Non-Technical Skills for Surgeons (NOTSS) [86] rating system designed for non-technical skills and the Observational Teamwork Assessment for Surgery (OTAS) [87] rating scale that assesses team performance. Guru et al. [88] have highlighted that assessment of cognitive abilities (i.e., processes involving information-gathering, visual scanning, and sustained attention) is a good marker of differentiation between beginners, competent, proficient, and expert surgeons. Nevertheless, it requires further research for external validation. It is clear that the design and development of a targeted, standardized, and integrated assessment tool remain an unmet need to reflect the capabilities of surgeons worldwide.

Future Directions

The scope for improvement in robotics in the field of neurosurgery is immense [33], however, communication latency remains one of the biggest hurdles to overcome in order to increase the scope of robotics in the field. Future advancements will be seen in sensors, computers, and manipulation components of surgical robots to improve the identification of tissues, nerves, blood vessels, and tumors. Advancing sensors for haptic feedback aim to address the primary complaints of surgeons. Another arena where technology is being advanced is manipulators and end-effectors [33]. Robots such as the da Vinci system are progressing to reduce their size and footprint within the operating room. This will make them more accessible, safer, and cheaper, increasing their adoption in years to come.

Shared control robots, rather than completely autonomous or dependent systems, will likely dominate the field as surgeons combine the sense of control with allowing robots to assist in pre-programmed ways [12]. The ability of some neurosurgical robots to assume autonomous tasks will continue into the future. Such abilities will include the use of artificial intelligence to automatically adjust cutting speed or applied force or will be able to sense delicate boundaries and warn surgeons before they proceed [5]. This will enhance our capability to operate in small spaces and reach previously "inoperable" lesions within the brain while simultaneously reducing the risk of harm to the patient.

In order to arrive to this state, surgeons need to be trained in a cost-effective manner on all aspects of robot-assisted surgery. Robotic simulators combined with AR/VR will continue to evolve to decrease the steep learning curve. At the same time, regulatory agencies will discuss standardization of credentials and residency programs to ensure all practicing robot-assisted surgeons are educated and trained equivalently.

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