2 Stereotactic Robots

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Introduction

The Robot Institute of America defines robots as a “reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks.” The use of robotics in functional neurosurgery holds large promise: robots have the potential to increase the accuracy and precision of targeting miniscule lesions and provide surgeons with increased dexterity via minimally invasive techniques to access important deep-seated anatomic structures in the brain in a safe and effective way. Robots confer the ability to perform complicated, often repetitive tasks, with great precision; it is for this reason that robots have garnered more widespread use in the subspecialty of functional neurosurgery. Given the increasing complexity of surgical procedures performed, the need for a high degree of accuracy in stereotaxy is well addressed by robotic solutions, which has led to their increased use in modern neurosurgical practice.

The use of robotic stereotaxy is the latest technology that builds on the historical trend of the need for improved anatomic and radiographic accuracy in the field of neurosurgery. Early forays into stereotaxy, dating back to the late 1800s, were constrained by the wide variability between bony landmarks and intracranial targets. Frame-based stereotaxy (detailed extensively in Chap. 1) dates back to the late nineteenth century, when it was first used by Gaston Contremoulins, a self-educated scientist, to remove two intracranial bullets [1]. Spiegel and Wycis further improved the use of stereotactic approaches for intracranial surgery in 1947, by pairing pneumoencephalograms with intracranial reference points [2]. The need for a reliable accuracy in stereotaxy naturally lends itself to the use of surgical robots. Nowadays, three-dimensional imaging is obtained that, in conjunction with stereotactic systems, is used to devise trajectories that allow for the precise targeting of intracranial structures. Robots can supplement the surgical workflow by having the surgical plan programmed into the machine, to be subsequently executed with robotic precision during the course of the surgery.

Robots may be integrated into a surgical workflow as either an active or passive system. An *active system* is one in which the robot can be manipulated in real time and interacts with the patient throughout the course of surgery as it is being wielded by the surgeon. A *passive system*, on the contrary, functions to hold a surgical tool in a predetermined fixed position in order to provide improved stability to the surgeon, with the

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surgeon ultimately actually carrying out the movements directly.

In addition to describing robotic systems as either active or passive, there are three broad categories which robotic systems may be categorized. A *telesurgical system* is one where the surgeon directly controls each movement of the machine; the robotic arm acts as a conduit for each manipulation performed by its user. The most well-known telesurgical system is the da Vinci system (Intuitive Surgical, Inc.; Sunnyvale, CA), which has garnered use across multiple surgical disciplines. The second type of system is a *supervisory controlled system*, in which the machine is pre-programmed with actions which are autonomously performed by the robot, under the close supervision of the surgeon. Lastly, *shared-control models* are systems that allow the surgeon and the robot to concurrently control the motions carried out during an operation [3].

The first use of a robot for a neurosurgical procedure was in 1985, via the Programmable Universal Machine for Assembly (PUMA) device, which represented a passive robotic system. A patient with an intracranial lesion was placed in a stereotactic head frame and underwent target localization using a CT scan. The target coordinates were programmed into the PUMA robot, aiding the surgeon to devise an accurate trajectory to the target lesion and also avoid critical structures along the biopsy path [4]. The MINERVA system, introduced in the 1990s, offered integration of a robotic system with CT guidance to allow a surgeon to monitor instrument position and progress in real time [5]. Although both of these early systems have since been discontinued, the last two decades have brought about an increasing number of innovative robotics designed to help carry out complex neurosurgical procedures.

Integration of robots into the neurosurgical operating room offers many benefits, but also has inherent limitations, for both the patient and the surgeon. This chapter will provide an overview of the use of robotics in the field of stereotactic and functional neurosurgery, including various types of robotic systems available for commercial use, its benefits and disadvantages, and its current and future applications for use in neurosurgical procedures.

Workflow of a Robotic Neurosurgical Procedure

The integration of robotic systems into the neurosurgical workflow presents both opportunities and challenges to the surgeon. Navigated and robotic systems achieve accuracy and workflow benefits using a series of accurate alignments between preoperative images, intraoperative tracking tools, and the patient's relevant anatomy. The following is an overview of the various stages of robot-assisted neurosurgical procedures, each of which must be carried out carefully in order to achieve accuracy and success.

Preoperative Three-Dimensional Imaging

The basis of image-guided procedures is the acquisition of a high-resolution three-dimensional (3D) image to delineate the relevant anatomy. This can be achieved via a CT scan, MRI, angiogram, an intraoperative tomographic scan, or a combination of these images fused together. It is important to note that the overall efficacy of a robotic system is limited by the quality and accuracy of preoperative imaging obtained: if slice thickness is too coarse or if there are significant imaging artifacts, both of which can limit the quality of 3D reconstruction, the achievable accuracy rendered by the robot may be compromised. Indeed, the capabilities offered by robotics and its ever-increasing use in neurosurgery have followed technical advancements in the quality of imaging surgeons are able to obtain.

Trajectory Planning

Based on the 3D anatomical image, the surgeon determines a desired trajectory, which encompasses the tract between the entry point and set target point. The planned trajectory should ideally avoid traversing through, or abutting, critical structures (such as blood vessels), sulci and ventricular system when possible, and important white matter tracts (see Chap. 5 for a more in-depth description). The preoperative imaging obtained allows the surgeon to devise trajectories using a probe's eye view, providing a view of the devised tract(s) in a reconstructed plane along the cross section of the trajectory. In the case of stereoelectroencephalography (sEEG), multiple trajectories have to be carefully planned to ensure that each one can be inserted safely and still be efficacious (see Chap. 23 for a more detailed discussion of planning invasive monitoring for epilepsy).

Registration

This is the key step that aligns the preoperative 3D imaging and planned trajectories with the actual patient position in the OR, by co-localizing a mutually reliable landmark appreciable on imaging and the patient's body itself. There are a number of different ways of achieving this registration, each with workflow and accuracy trade-offs. Options include mechanical based surface registration using facial features or bone fiducial registration (where a surgeon uses a probe to specify the location of anatomy, which is co-localized on the preoperative image). The use of frame-based or bone fiducial-based registration confers a higher degree of accuracy between preoperative imaging and intraoperative position [6].

Delivery

Once the preoperative plan has been registered to the intraoperative patient anatomy and position, the robot is used to execute the preplanned trajectory by moving its surgical arm into the correct position. Accuracy of the overall operation also relies on the accuracy of all prior steps and the precision in this step – ensuring the robot is holding the guide in the proper position relative to the plan. This is especially true when multiple trajectories are being executed for the placement of several leads, where each subsequent one is subject to small changes in cerebral surface locations (brain shift) [7], owing factors such as cerebrospinal fluid egress, pneumocephalus, and gravitational effect.

Postoperative Verification

After completion of the surgical procedure, it is important to verify the accuracy of the delivered plan, not only to evaluate the accuracy and efficacy of the surgery itself but also to quantify any errors with the intent to correct for them in future procedures. Systematic errors within an institutional system (which can be different based on target and application) can and should be recognized and compensated for based on continuous assessment and implementation of corrective measures.

Clinical Applications of Robotic Stereotaxy

Recent technological advances in surgical robotics have heralded its use for a wide range of neurosurgical procedures, including stereotactic biopsies of tumors [5], deep brain stimulation (DBS) electrode placement [8], placement of sEEG electrodes for evaluation of medically intractable epilepsy [9], ventricular catheter placement [10], and laser ablation procedures [11]. This section provides an overview of the various stereotactic procedures that have successfully incorporated the use of robots into neurosurgical workflow with excellent results.

Stereotactic Biopsies

Frame-based stereotactic biopsies have been the gold standard for deep-seated lesions that are not amenable to open surgical biopsy or resection, in order to provide a histopathologic diagnosis that is used to guide further treatment. Over the past decade, stereotactic robots have been used to perform these biopsies, using both frame-based and frameless methods.

One study of 15 biopsies of brain stem lesions using frameless robotic stereotaxy yielded an 87% success rate of histopathological diagnosis on the first attempt. Out of the adults who underwent robotic-guided biopsy, two experienced transient neurological deficits, and one patient suffered permanent deficit [12]. A separate study found a diagnostic yield of 99% for pineal-area lesions [13]. In recent systematic review of 15 publications encompassing a total of 328 robotic brain biopsies performed, Marcus et al. found a diagnostic yield of 75–100%, with a target-point accuracy ranging from 0.9 to 4.5 mm. Taken together, these findings give credence to the use of robots to safety and efficiently perform intracranial biopsies, with or without the use of frame-based systems [14].

DBS Electrode Implantation

The targeted ablation and implantation of electrodes into deep-seated brain nuclei have significantly impacted the treatment of movement and neuropsychiatric disorders such as Parkinson's disease, essential tremor, and medically refractory depression. The efficacy of DBS treatment is predicated upon the accurate placement of leads within the target brain nuclei, with a target-point error of under 3 mm that is often required [15]. Robots are uniquely suited to help carry out placement of DBS leads, primarily owing to its ability to modify the entry and target points without onerous manipulation associated with utilizing frame-based systems.

Frame-based stereotaxy has historically been the gold standard for achieving accuracy in DBS electrode implantation [16]. Differences in stereotactic accuracy and methodology between frame and frameless systems are discussed in Chap. 1. One should be cognizant though that while there may be differences in stereotactic accuracy, these differences may not translate into clinically meaningful differences [17]. Still, as a principle, stereotactic surgeons strive to achieve stereotactic accuracy under all circumstances.

Robots may offer specific advantages for implantation of DBS leads because of their fidelity to carry out planned trajectories whether using frame-based or frameless system. In a study that evaluated the accuracy of DBS lead placement in 30 basal ganglia targets, the in vivo accuracy using a robotic system was found to be within 1 mm of the intended target, comparable to the accuracy conferred with using stereotactic frames [18]. Varma et al. published a single-institution case series of 113 DBS lead placements using a robotic system, reporting a mean error of 1.7 mm from the intended target-point placement, and only in three cases was the deviation greater than 3 mm. Highlighting the importance of assessing functional differences that may result from differences in stereotactic accuracy, patients undergoing DBS placement using a robot were found to have improved activity of daily living (ADL) scores and significant improvement in their motor fluctuations that persisted at 18 months follow-up, results similar to those reported previously using traditional frame-based stereotaxy [19].

sEEG Electrode Placement

The placement of sEEG electrodes serves as an option for the workup of drug-resistant epilepsy when the epileptogenic focus cannot be identified via noninvasive approaches and when invasive monitoring is necessary. The ability to place multiple sEEG electrodes helps encompass both cortical surface and deep matter structures, from which real-time electrophysiological activity can be recorded. The need to place multiple leads within deep-seated areas of the brain while avoiding critical structures along each planned trajectory is repetitive, time-consuming, and prone to error due to the need for constant human intervention and adjustments of frame coordinates. This presents a challenge that robotic systems are uniquely well-suited to help address. Robots are indefatigable; the ability for them to execute trajectories that have been planned by the surgeon in advance of the day of surgery carries a lower chance of misplaced leads, thereby decreasing the risk of perioperative complications and operative times. As such, the placement of sEEG electrodes represents the most commonly performed functional neurosurgical procedure for which robots are utilized [20].

The earliest reported use of robotic-assisted implantation of sEEG electrodes was in 2005 by Cossu et al.: 17 out of 211 patients underwent placement of sEEG electrodes using a robot, and the remainder were implanted manually using the traditional stereotactic frame-based methodology, with similar rates of seizure freedom between the two groups [21]. In a separate study evaluating placement of 1050 sEEG leads using robotic assistance in 81 patients showed a 6% risk of perioperative minor complications without any mortalities, comparable to manual lead implantation. The median target-point error was found to be 1.77 mm for robotic cases, significantly lower compared to those inserted manually (2.69 mm) [22]. Given the similar accuracy and rates of complications, these early case series gave credence to the use of robotics for sEEG placement, prompting more surgeons to adopt its use in the operating room.

Abhinav et al. chronicled their initial experience after adopting the use of a robotic system for implanting sEEG leads in five adults and found that their total operative time was higher (mean 5.6 hours compared to 3.1 hours), owing to the implementation of an entirely new surgical workflow [23]. A more recent study that evaluated the efficacy of implanting sEEG leads using the ROSA robot found similar rates of complications between the robotic-assisted patient cohort (4%) compared to leads inserted manually using a frame-based technique (3%); however, the use of the robot resulted in markedly decreased surgical times by a mean of 222 minutes. Of the patients who subsequently underwent resection of seizure foci based on their sEEG findings, 66% were seizure-free at 18 months follow up [24]. Taken together, these results, along with other case series that have showcased similar results, demonstrate that robotic-assisted sEEG lead placement is a safe, effective, and efficient technique for evaluation of epileptogenic foci and accounts for the most commonly performed robotic procedure in the field of functional neurosurgery.

Laser Ablation of Intracranial Lesions

Stereotactically applied laser interstitial thermal therapy (LITT) using real-time MRI guidance has been used to treat a wide variety of pathology, including epileptogenic foci and deep-seated intracranial lesions [25]. The success of these procedures necessitates accurate placement of the focus of the laser treatment within the core of the intended target. As such, the use of robotic systems has been shown to be a safe, efficient, and minimally invasive treatment to achieve surgical success.

Calisto et al. published their short case series on robotic-guided LITT of hypothalamic hamartomas. Although the study did not discuss the accuracy of lesion targeting, they found the procedure to be a safe and effective means of achieving seizure freedom, with 15.4% of patients having mild memory impairment postoperatively [26]. Gonzalez-Martinez et al. published their operative technique whereby they utilized a robotic system to guide placement of a laser catheter into the target epileptogenic lesion located adjacent to the right frontal horn and caudate nucleus. Interestingly, this proof of concept arose from the authors' familiarity and success of using a robotic system for placement of sEEG electrodes at their institution [11]. Thus, it is feasible that as robots gain more widespread use and surgeons become more familiar with its use, robots will become more frequently used in a wider variety of stereotactic procedures.

Robotic Systems

Three major robotic systems are used commonly for intracranial applications. This section will focus on providing a brief overview of the workflow and capabilities of each robotic system intended for intracranial use.

Neuromate Robot (Renishaw)

The Neuromate robotic system by Renishaw (Wotton-under-Edge, UK) gained FDA approval

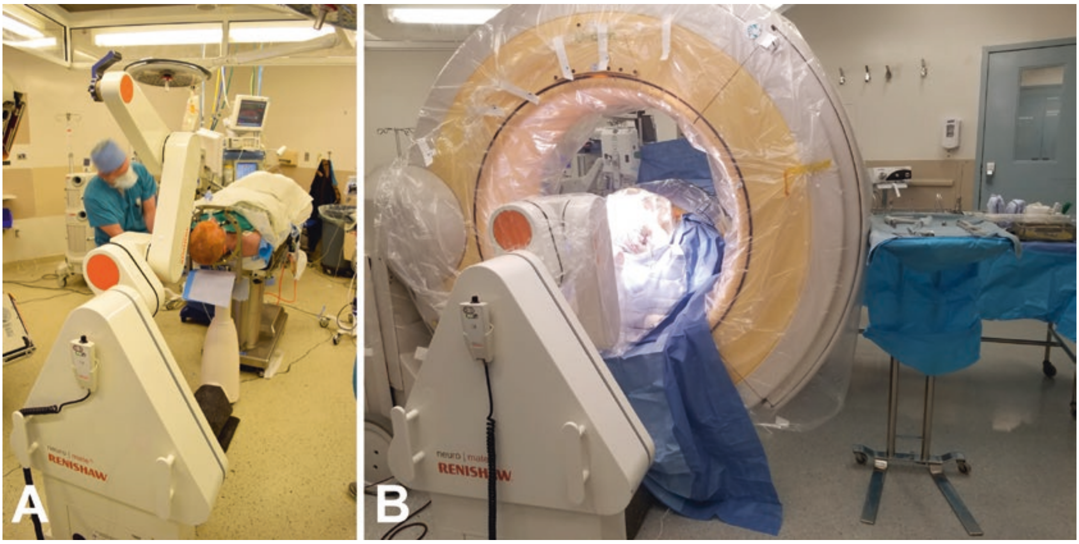

Fig. 2.1 The Neuromate robot gained FDA approval for intracranial procedures in 2014. (**a**) The patient is affixed to the robotic platform at a fixed length, and registration can be performed via frame-based or frameless applications. (**b**) An O-arm is often used in conjunction with the robotic system, which requires copious operating room space, and limits the space available for surgical staff while carrying out the procedure

for cranial procedures in 2014. The Neuromate robot provides surgeons five degrees of freedom and serves as a platform to carry out a broad range of intracranial stereotactic applications (Fig. 2.1).

Preoperative MRI scans, which may be supplemented with functional, vascular, or bone imaging, are used to plan trajectories to intracranial structures/lesions of interest in advance of the date of surgery. Registration can be performed using a conventional stereotactic frame fiducial box or a frameless registration module. When a fiducial box is utilized, the workflow consists of the following steps: the frame is affixed to the patient's head; a volumetric CT scan is acquired with the fiducial box on (usually in a diagnostic CT suite); the fiducial rods are automatically or manually localized using the planning software; once in the operating room, the patient's head is fixed directly to the base of the robot via the stereotactic frame, thereby securing the cranium at a fixed and predetermined length from the base of the robotic arm. The workflow for the frameless method is somewhat different. The frameless registration module consists of five synthetic round fiducial markers and carbon fiber rods that are attached to the laser holder and the robot arm. Once the patient is in the operating room, these fiducial markers are positioned closely to the head and an intraoperative CT scan is acquired. Finally, the stereotactic planning software identifies the center of each fiducial mark and registration is complete. When the robot is activated by the surgeon, the pre-entered coordinates direct the robotic arm into the correct entry point and target angle. The surgeon then inserts the leads to the targeted depth (this has also been calculated during preoperative planning, based on the distance from the target that the robotic arm is set), with the robotic arm providing improved control and stability. This process can be repeated, as necessary, for all leads that are intended to be implanted.

The entry- and target-point error rendered by the Neuromate robot has been studied and corroborated in a several studies investigating its use. In one study, entry-point error for frame-based application using the Neuromate robot was found to be 2 mm or less [22]. Frame-based target-point error has been reported to be between 0.86 and 1.77 mm, conferring a slightly higher accuracy compared to frameless application [18, 19, 27].

Renaissance Guidance System (Mazor Robotics)

The Renaissance guidance system from Mazor (Caesarea, Israel) provides the surgeon with six degrees of freedom. It was initially designed for use in spine surgery, gaining FDA approval for this application in 2004, before it was expanded for use for intracranial stereotactic procedures in 2012 (Fig. 2.2).

The Renaissance robot cannot be used in conjunction with traditional frame-based stereotaxy. Instead, a platform marker is mounted to the skull to serve as a surface marker, and an intraoperative CT scan is obtained. These images are then co-registered with a preoperative MRI, thereby allowing the software to interpret planned trajectories devised preoperatively in conjunction with the reference platform. Then, the guidance unit, which is the size of a beverage can, is affixed to the platform; the Renaissance system provides 360° working volume to access and execute various entry- and target-point trajectories, as needed. At the same time, this design serves as a limitation of the Renaissance system, as it cannot be used for sEEG implantation, owing to the limited reach of its robotic arm.

At the time of publication, there have been no peer-reviewed articles published on the accuracy of the Renaissance robotic system; however, in a white paper published in 2014 that outlined a retrospective case series of 20 subthalamic nucleus (STN) implants at a single institution, the mean target-point error was found to be 0.7 +/− 0.36 mm, lower than using a Leksell frame (1.7 +/− 0.6 mm) [28].

ROSA (Zimmer Biomet)

The ROSA robot from Zimmer Biomet (Warsaw, Indiana, USA) gained FDA approval for cranial surgery in 2010. The ROSA affords the surgeon six degrees of freedom. The ROSA robot is the only available system that can be used for endoscopy procedures in the United States, thereby

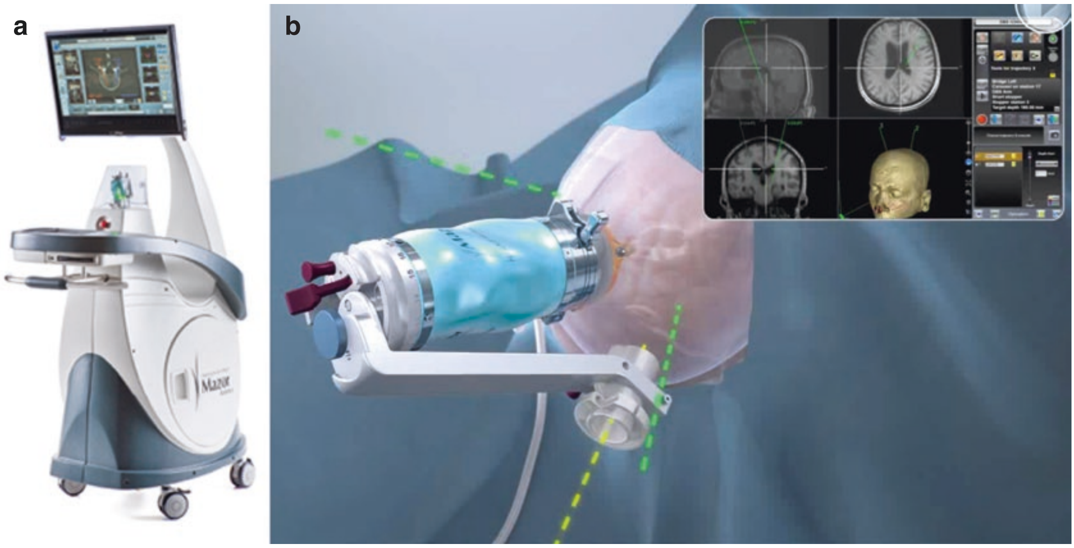

Fig. 2.2 The Renaissance robotic platform robot gained FDA approval for cranial surgery in 2012. (**a**) The Renaissance robotic platform provides its own software which can be used to co-register preoperative imaging with an intraoperative CT scan. (**b**) A small reference frame is affixed to the patient's skull, and then a guidance unit, which contains the robotic arm, is secured to the base. The small, frameless platform utilized by the Renaissance robot provides a 360 degree working volume, allowing for the execution of a wide range of planned trajectories

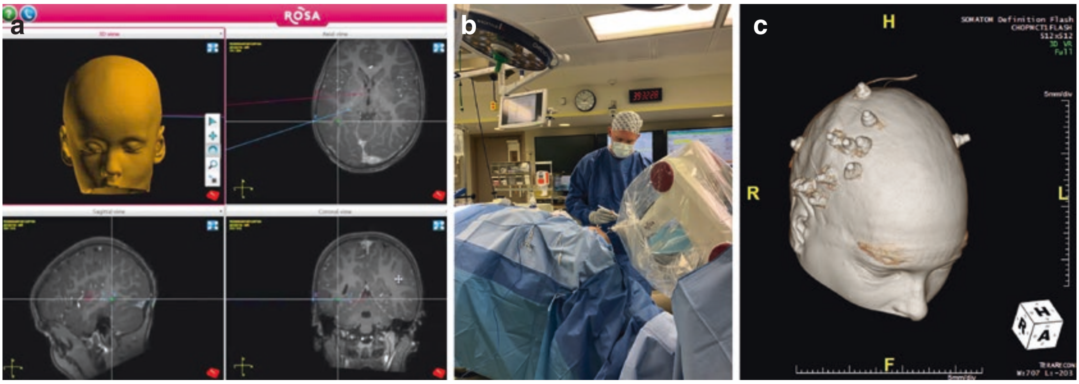

Fig. 2.3 The ROSA robot gained FDA approval for cranial surgery in 2010 and exists as a free-standing system. (**a**) The ROSA robotic system provides its own software that can be used to plan trajectories preoperatively. (**b**) In the operating room, the ROSA system provides haptic feedback while carrying out the surgical procedures, affording the surgeon to manipulate the arm directly to its desired location. (**c**) The ROSA robot has been used extensively for placement of sEEG leads

reducing the risk of traction-related injuries by providing a stable mechanical holder for the endoscope [29] (Fig. 2.3).

Like the other robotic systems, the surgeon plans entry-point and target trajectories preoperatively. The ROSA system also offers frame and frameless registration methods. For the frame-based approach, the robot captures points on a specific case that is attached to the frame. For the frameless approach, the ROSA system offers its own unique laser registration system that automatically captures individual points on the patient's face and forehead. After registration is complete, the robot can be locked in position at a fixed distance from the patient's skull, in order to maintain accuracy throughout the duration of the surgery. The ROSA system is the only robot that provides haptic feedback to the operator, thereby allowing the surgeon to directly manipulate the robotic arm in any desired direction, in a manner analogous to a stereotactic arc.

The ROSA robotic system has been shown to be a highly effective stereotactic system with a wide range of clinical applications, including LITT, responsive neurostimulation, and sEEG [30]. In one study evaluating sEEG electrode implantation, entry-point error was shown to be less than 2 mm in more than 90% of cases, and targeting error is less than 2 mm in 83% of cases [24]. Another single-institution case series evaluating placement of 222 sEEG leads in pediatric patients (mean 11.1 leads per patient) reported a mean radial error of 1.75 +/− 0.74 mm, with no associated postoperative complications from lead placement and monitoring. The mean total case time was 297.95 ± 52.96 minutes, and the mean operating time per lead was 10.98 minutes, with improvements in total (33.36 minutes per lead vs 21.76 minutes per lead) and operative (13.84 minutes vs 7.06 minutes per lead) case times/lead over the course of the study [31].

Advantages of Robots

The integration of robots into neurosurgical procedures offers many benefits for both the patient and the surgeon. Robots inherently provide their operator the ability to carry out repetitive tasks in a safe and efficient manner, provided that the plan programmed into the system is accurate. In a stereotactic surgery, each trajectory employed requires adjusting and conforming various coordinates in order to ensure its correct placement. As the number of trajectories increases, so, too, does the opportunity for error. Robots can decrease this risk of error by limiting the amount of human manipulation and transposition of the operator arm. Furthermore, by setting up the workflow such that the entry- and target-point coordinates are entered into the robot preoperatively, the error associated with interpretation of frame coordinates during the surgical procedure itself is reduced as well.

The use of frame- and arc-based systems for stereotactic localization of target points does, in fact, confer a high degree of submillimeter precision, and this system has been used widely prior to the advent and adoption of surgical robots. However, their existing design in which the entry point of a trajectory is determined by the less precise arc and ring coordinates serves as a major limitation, owing to the higher degree of human interpretation inherently present while adjusting settings. There are a few studies that have compared the accuracy of entry-point error between frame-based systems and robotic systems, each of which has shown a comparable error rate (less than 2 mm in most cases), thereby showing its reliability in executing the planned trajectories [32].

Current frame- and arc-based systems limit the surgeon's choice of entry points. In sEEG implantations, for example, in which the trajectories are oriented in a lateral to medial, there is a need to be able to plan trajectories that start from a more caudal position. The Leksell frame offers an entry point within an arc of 170°, slightly better than utilizing a CRW frame, which confers an arc range of 120°. Depending on the configuration of the arc of the frame, collisions between the platform and the frame base limit the extent of trajectories that can be planned compared to those feasible with a robot.

Once a surgical team has learned how to effectively employ robotic systems to their surgical workflow, this should lead to decreased total surgical times. Indeed, the value of decreased OR time is not insignificant; one study cited an average decrease in OR time of over 3 hours when compared with traditional stereotactic frames [24]. Decreased length of surgery also serves to reduce surgeon fatigue and, ultimately, to minimize the risk of incurring adverse events, including postoperative infections.

An additional advantage to adopt robotics into neurosurgical practice is the ability to boost the commercial appeal of the hospital and perception of the procedure itself. The term "robot" leads patients to perceive that the procedure itself is cutting edge and to the reckoning that the hospital must be on the forefront of innovation and technology. A recent study quantified the effect of marketing robotic surgery as "innovative" or "state of the art" and found that greater than 30% of patients would choose to undergo a novel procedure over a conventional alternative if it was framed in this manner [33]. As such, if the safety and efficacy of both conventional and novel techniques are at least equal, providing the "state-of-the-art" robotic alternative may provide not only a marketing advantage but also greater confidence in the surgeon's capabilities.

Disadvantages of Robots

Although robots have been utilized with increased prevalence in neurosurgical practice, adopting their use presents its own set of challenges. The operating room itself has to be spacious enough to house the robot system and to accommodate the surgeons, anesthesiologists, nurses, techs, and company representatives involved in the case. Furthermore, there is a learning curve associated with the adoption of the robotic system in the operating room. For intracranial procedures such as DBS and sEEG electrode placement, the surgeons and the support staff must be familiar with the nuances of incorporating the robot into the surgical procedure, which includes sterile draping of the robot, understanding when and where the robotic arm should and should not move, and how to preserve efficient instrument passing between the operator and assistant(s) within the constraints of the limited workspace around the patient and robot position. Like any piece of complex machinery, robots are susceptible to malfunctioning, which can occur at any stage during a procedure. Furthermore, its calibration may become less precise over time, compromising its accuracy. As such, regular servicing and maintenance must be scheduled.

Frame-based systems offer a real-time verification of target engagement through the use of cross hairs and fluoroscopy. Robotic systems do not have similar accessories; thus, unless an intraoperative CT scan is obtained, the plan executed by the robot is inherently reliant on the accurate imaging fusion and registration. Indeed, one may utilize a frame in conjunction with the use of a robot, thereby affording the surgeon to corroborate the target point manually by setting the coordinates of the frame, but doing so negates the increased efficiency conferred by utilizing a robotic system.

Purchasing a robotic system for use at a hospital carries a steep expenditure upfront and subsequent costs for proper maintenance and servicing of the robot and its software [34]. These costs, however, must be weighed against the savings achieved by reducing total operating room time. Three years after adopting a robot at our institution, our surgical time for placement of bilateral DBS leads and battery typically spans just over 2 hours, and the placement of 10–16 sEEG leads clocks in at around 3 hours, considerably shorter than when these procedures were carried out manually using frame systems. Thus, it is our belief that the adoption of robotic systems into an established neurosurgical practice confers a wide range of benefits and, despite the financial costs associated with it, provides great potential for its use in a variety of procedures.

Conclusions and Future Directions

In recent years, an increasing number of robotic systems have been designed for and integrated into neurosurgical practice. In the field of functional neurosurgery, which has historically relied on the use of stereotaxy for the localization of intracranial targets, the implementation of robotics in the operating room has provided surgeons the advantage of improved accuracy and safety, with less damage to critical surrounding structures, and, ultimately, favorable clinical outcomes.

As more neurosurgeons adopt the use of robotics, new advancements in the technology available will continue to take shape based on refinements and suggestions that serve to improve surgical workflow. As technology continues to improve, combined with the feedback provided by a larger cohort of neurosurgeons using robotic systems, the overall user experience will also continue to improve. For example, miniaturization of components will lead to a decreased robotic footprint and increased portability; and improved sensors and applicators will further enhance the capabilities and skills of surgeons using these systems. Such advancements will also improve the reliability and longevity of robotics, thereby reducing overall costs. Furthermore, improved user interfaces will make integrating robotics into neurosurgical practice more intuitive, with improved automation of perioperative tasks.

Finally, ongoing development may also push robots into a greater role in surgical education as robots with improved visual and haptic feedback can be used to create realistic surgical stimulators. There are a few published studies that suggest that training with robotic technology may shorten the learning curve for surgeon trainees and decreases the learning curve for the acquisition of new surgical skills [35]. The ability to use traditional frame-based methods in conjunction with certain robotic systems also ensures that trainees are still taught how to carry out procedures without robotic assistance and may lead to a greater appreciation of the benefits robots provide. Indeed, the integration of robots into the neurosurgical operating room offers many benefits for both the patient and the surgeon, albeit it requires the development of a new operative workflow. We believe that continued innovation and technical advancements will make robots more prevalent for use in a variety of surgical procedures and foresee its use becoming more mainstream in the field of functional neurosurgery.

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