Sofía Cáceres Nazario. *Muscovy Ducklings*, 2015 (Detail). Acrylic on canvas, 12" × 16".

Robotic-assisted neurosurgery may help increase accuracy and allow surgeons to perform more complicated operations.

Robotics in Neurosurgery: Evolution, Current Challenges, and Compromises

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Background: *Advances in technology have pushed the boundaries of neurosurgery. Surgeons play a major role in the neurosurgical field, but robotic systems challenge the current status quo. Robotic-assisted surgery has revolutionized several surgical fields, yet robotic-assisted neurosurgery is limited by available technology.*
Methods: *The literature on the current robotic systems in neurosurgery and the challenges and compromises of robotic design are reviewed and discussed.*
Results: *Several robotic systems are currently in use, but the application of these systems is limited in the field of neurosurgery. Most robotic systems are suited to assist in stereotactic procedures. Current research and development teams focus on robotic-assisted microsurgery and minimally invasive surgery. The tasks of miniaturizing the current tools and maximizing control challenge manufacturers and hinder progress. Furthermore, loss of haptic feedback, proprioception, and visualization increase the time it takes for users to master robotic systems.*
Conclusions: *Robotic-assisted surgery is a promising field in neurosurgery, but improvements and breakthroughs in minimally invasive and endoscopic robotic-assisted surgical systems must occur before robotic assistance becomes commonplace in the neurosurgical field.*

Introduction

The concept of robots has evolved from "human-like" machines to programmable, multifunctional specialized devices. Today robots are highly specialized machines used in a diversity of fields, particularly in industrial applications in which their speed and accuracy present recognizable advantages. In the surgical field, it was not until the mid-1980s when surgeons utilized the concept of robotics for the first time with a device used to perform precise biopsy in neurosurgery.[1] Since then, manufacturers have made efforts to improve the efficacy and reliability of their robotic systems.

The first application of robotic-assisted surgery was in the neurosurgical field, but robotic advancements in urology, gynecology, gastroenterology, and orthopedics are more common due to fewer anatomical challenges. For example, a large cavity where a robotic arm could be used to assist in spine surgery is nonexistent, and brain surgery involves delicate neural structures and approaches through narrow surgical corridors where manipulation and space are both limited.

This article provides an overview of the origin and evolution of robotic-assisted surgery, with a special

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focus on the current robotic systems in use, advancements, limitations, and future developments of neurosurgery.

Classification

A surgical robot is any reprogrammable-powered manipulator with artificial sensing that can assist in a variety of surgical tasks.[2] Since the development of this concept, others have suggested different classifications in terms of the technology, applications, and roles of the robot during surgery (Table).[2-7] The device's function/application and the degree of surgeon–robot interaction are important factors to consider in any classification, particularly because these 2 features may drive the future development of surgical robots.

The amount of interaction the surgeon receives from the robotic system during surgery is crucial. If the surgeon does not need to interact with the robotic system during surgery, then more trust is placed on the robot. In this type of situation, surgical success depends on the development of the robot, where less control can equate to increased risk if the robot is improperly programmed. Nevertheless, the amount of surgeon control determines the responsible parties, the risk in the operating room, and the classification function of the robot.

The type of function and application relies on the type of robot. In general, 3 basic types of robotic systems exist: autonomous, dependent, and shared control. Autonomous systems reproduce programmed motions or move the system to set locations by calculating the required position. The most common neurosurgical application of an autonomous system is stereotactic positioning. Dependent systems, also called master/slave systems, are the most popular type of robotic system because the surgeon maintains full control of the system at all times. These types of systems allow surgeons to perform remote surgeries, sometimes referred to as telesurgery. Shared-control systems are a hybrid between the dependent and autonomous systems. For example, a shared-control application could involve a passive arm hooked up to a surgeon's hand that moves only when permitted, but yet it can filter unwanted motions such as hand tremors.

Evolution

Although the concept of robotic surgery was first seen in the neurosurgical field less than 30 years ago, robotic technology continues to progress in the medical field. The first robot used in neurosurgery was the PUMA 200 (Unimation; manufacturer defunct) for stereotactic surgery.[3] The system allowed the placement of a biopsy needle in the brain using computed tomography (CT) guidance. The robot had the potential to deliver faster results than any other procedures available at the time that required the manual adjustment of the stereotactic frame because its computer calculated faster than humans. The device has been since discontinued, but the PUMA 200 is considered to be the pre-

Table. — Classification of Surgical Robots

Study	Type	Classification	Description
Davies[2]	Position control	Active	Interact with patient during surgery
		Passive	Can be powered off after robot achieves target position
Taylor[4]	Role based	Intern replacement	Specific surgical interns serve as role substitutes
		Telesurgical	Controlled by the surgeon throughout the procedure
		Navigational aid	Computer-assisted system integrated with imaging
		Precise positioning	Navigational aid with own motive power
		Precise path	Precise positioning that moves tool through a predetermined path
Camarillo[5]	Role based	Passive	Limited scope Low risk
		Restricted	Greater scope Higher risk than passive
		Active	Greatest involvement Highest risk
Bann[6]	Function	Dexterity enhancement	Equivalent to telesurgical method[4]
		Precision location	Equivalent to precise positioning systems[4]
		Precision manipulation	Equivalent to precise path systems[4]
	Technology	Autonomous	Performs a preoperative plan programmed by the surgeon
		Supervisory	Serves as a guide during surgery
		Teleoperated	Equivalent to telesurgical method[4] Enhanced dexterity[6]
Nathoo[7]	Technical	Active	See description in Davies[2]
		Passive	Surgeons provide motive force to achieve target position and robot is then powered off
	Interaction	Supervisory controlled	Equivalent to autonomous method[6]
		Telesurgical	Equivalent to supervisory method[6]
		Shared control	Equivalent to telesurgical method[4] Enhanced dexterity[6] Teleoperated[6]

Information from reference 3.

decessor of most surgical robots.

Some commonly used robots available for neurosurgery are the neuromate (Renishaw Mayfield, Lyon, France), Pathfinder (Prosurgics, High Wycombe, United Kingdom), the NeuroArm (University of Calgary, Calgary, Alberta, Canada), the SpineAssist (MAZOR Robotics, Orlando, Florida), and Renaissance (MAZOR Robotics). The neuromate is a stereotactic system with 6 degrees of freedom (DoF) originally developed by Integrated Surgical Systems (Sacramento, California) in 1987, and the most recent version of the neuromate from Renishaw received US Food and Drug Administration (FDA) approval and is now commercially available (Fig 1). According to the manufacturer, neuromate can be used for several neurological applications, including deep brain stimulation, endoscopy, and stereoencephalography, and it is an efficient and safe instrument for biopsies in clinical cases.[8] Similarly, the Pathfinder is a stereotactic system that has proven accuracy in clinical research.[9] These 6-DoF robotic-arm systems differ from other neurosurgical robots because they use identified reflectors attached to the head of the patient that use a camera system instead of radiological, ultrasonographic, or mechanical guidance.[9]

The NeuroArm is a magnetic resonance imaging (MRI)–compatible surgical robot developed by the University of Calgary in 2001 (Fig 2).[10] It allows the surgeon to perform skilled tasks while located in a different location than the operating room and is commonly referred to as telesurgery. The system is capable of needle insertion, cutting, cauterization, and irrigation on a microscale (microsurgery) while simultaneously obtaining MRI. In 2008, NeuroArm was used for the first time to remove a brain lesion in a 21-year-old patient.[11] Since then, early clinical reports, which include various cranial neoplastic cases, show favorable results for the NeuroArm working station.[10,12]

In the spine surgery field, the SpineAssist received FDA approval in 2011 and is considered to be the first neurorobot to incorporate a module for minimally invasive surgery.[13] This specialized device is accurate and designed to offer a less-invasive solution for spine surgery, reduced complication rates, and limited recovery time; it may also offer fluoroscopic-guided surgery.[14] Despite its advantages, clinical evidence suggests that the nonassisted conventional technique has better accuracy rates; in addition, technical difficulties with robotic-assisted surgery suggest the presence of fluoroscopy backup,[15,16] although more evidence may be needed to determine whether a difference exists between assisted and nonassisted techniques.[17]

The da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California) is a robot used in urology, but its popularity is not matched in neurosurgery. The system has 4 arms, each with 7 DoF, controlled by 2 working arms and a 3-dimensional (3-D) stereoscopic view of the field that surgeons can use in a telesurgical manner (Fig 3). This robotic system has been used for transoral odontoidectomy, intrauterine repair of myelomeningocele, and spinal schwannoma

Fig 1. — The neuromate (Renishaw Mayfield, Lyon, France) is a stereotactic system used in various neurosurgical targeting applications. Image courtesy of Renishaw, Inc, Hoffman Estates, IL.

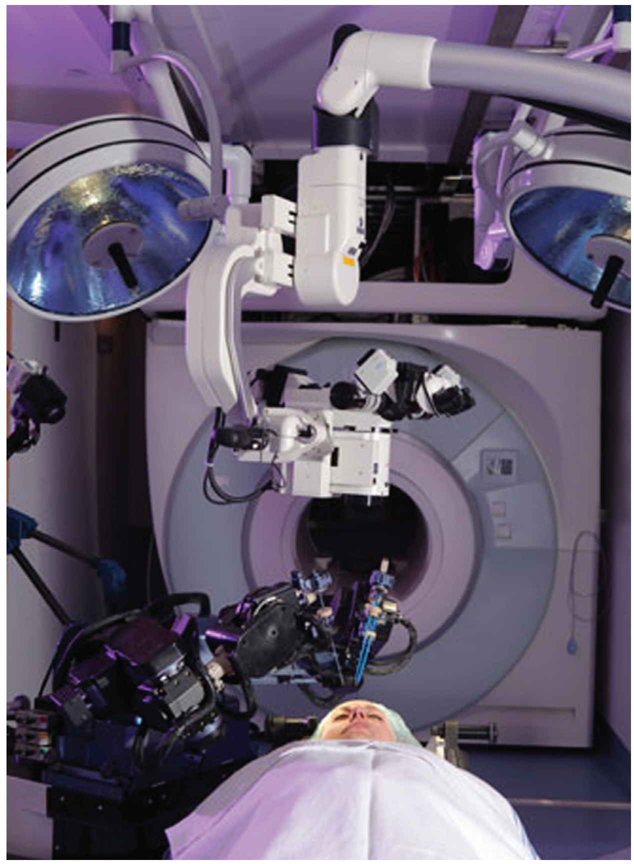

Fig 2. — NeuroArm (University of Calgary, Alberta, Canada) is a magnetic resonance imaging–computable master/slave system capable of several surgical tasks. Image courtesy of University of Calgary.

resection.[18] The feasibility of the system in a supraorbital keyhole approach for skull base tumors and aneurysms is also possible.[19] However, despite its success in various fields, the system has minimal impact in microneurosurgery because of the limited tools available, the number of ports needed, and the manipulation room and size of the system interfere with its integration into this field of neurosurgery.

According to Marcus et al,[20] the Steady Hand System (Johns Hopkins University, Baltimore, Maryland) is the only version of a shared-control system used in microneurosurgery. The main focus of this system is to filter out unwanted forces or motions, such as hand tremors, so that the surgeon can have the familiar feel of surgery with the accuracy and precision of a robotic system.[21] This system may have advantages in neurosurgery, but research on this system has been limited to retinal microsurgery.[22]

When designing a surgical robot, the features of each element depend on its specific application. Each design has an impact on the branches of neurosurgery (brain, spine, and peripheral nerve) and neuro-oncology, but the main focus of this article is endoscopic and stereotactic brain/neuro-oncology applications. Nevertheless, understanding the needs in specific fields and the anatomical constrains are crucial for optimizing the performance of the robotic system.

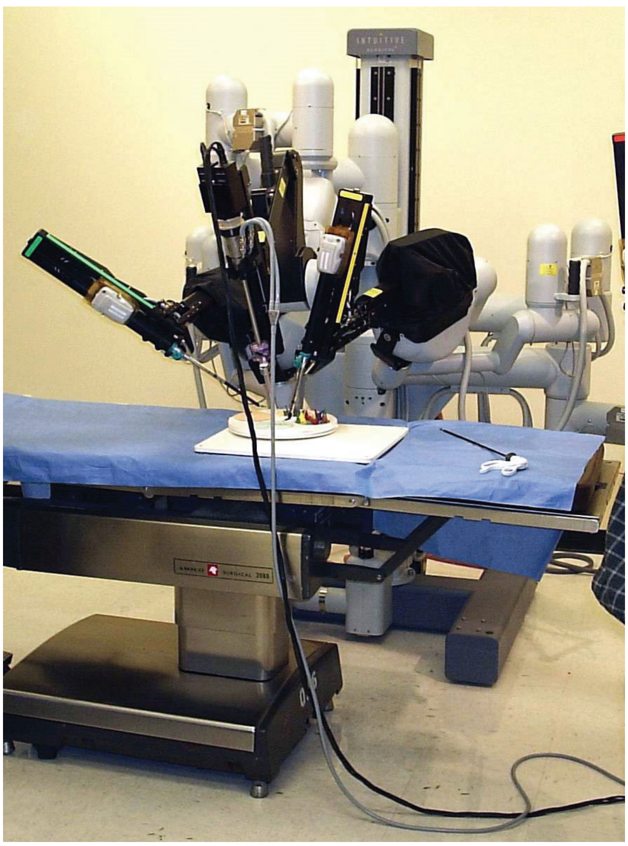

Fig 3. — Surgeons can operate the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) by controlling the robotic arms from a separate computer console connected via cables. © 2006–2015 Nader Moussa, Sunnyvale, CA.

Mechanical Factors

Mechanical factors are constraints placed by the manufacture on any part of the robotic system. The design of these parts dictates the function and application of the system. In general, relevant factors are in the tool and arm portions of the machine because they represent the closest interaction points of the surgeon.

Rigid Tools

Straight, long, and rigid manipulators with a clamp on the end are among the most common tools. Surgeons use them in endoscopic surgeries, but they also use the DoF of their hands to move them in space. By contrast, robots require additional DoF in the tool itself so that the robot can move the tool around in space. The general requisite is 6 DoF to move in a 3-D environment, yet the approach of rigid tools is limited to a straight line. Typically, rigid tools with multiple DoF effectors are the standard set of equipment for robotic systems, but engineers can still make advancements in tool design.

Curved Tools

Concentric tube tools are commonly used in autonomous robotic-assisted surgery. A concentric tube tool has several tubes nested inside one another and can be elongated in a telescoping fashion. This technology is useful when navigating confined areas (eg, performing transnasal sphenoidotomy for pituitary resection).[23]

A straight line is the closest distance between 2 set points, but a vital obstacle may be between those points. One of the challenges of brain tumor resection is the location of the tumor, where it can be semi-surrounded by sensitive tissue and the anatomy forces the approach through it. Thus, maneuvering in relative safe areas with these tools is optimal and possible.[24] Neurosurgeons can benefit from using these tools and techniques for transnasal approaches, biopsies, and endoscopic craniotomies to minimize invasiveness and reduce recovery time, particularly for cases requiring tumor removal. For example, imagine a small mass superior and lateral to the hippocampus that requires the surgeon to create a path through the temporal portion of the brain. With a curved-guided system, the surgeon could approach the lesion without extensively disrupting the brain tissue.

Concentric tube–curved tools have several benefits but also present technical challenges.[25] The calculation of where the tip is located is relatively simple with kinematic or Jacobian calculations, but only if the tool is rigid (unbendable). However, minimal tool diameters reduce the invasiveness of the procedure, creating nonrigid (bendable) pieces; thus, the tip location depends on the Jacobian calculations and on the deformation from the applied stresses. This, in turn, complicates how to determine the position of the device. Gilbert et al[25] showed that several ways exist for getting around this issue, ie, imaging guidance, magnetic/fiber-optic shape sensing, and force sensing.

Limited DoF with the manipulator are another limitation that hinder what can be done with these types of tools after the concentric tube is in position. Some manipulators, such as clamps, require a tension wire, but this tension can cause the curved tool to deform; this in turn limits the applications of such curved tools. However, curved tool applications have benefits in some removal techniques, such as suction, and, in particular, brain tumor removal and biopsies.

Compromises

The challenges of tool design for endoscopic, minimally invasive, and robotic-assisted surgery are similar. The surgeon must be able to operate the tools in confined spaces. If the tool is too large, then it will crowd the space; by contrast, if it is too small, then the tool will be difficult to control. Thus, its design requires a balance between strength and size. The type of stress the tool is under is also another parameter that determines where the strength needs to be. Stress is closely related to the end effector because it determines how the surgeon must move the tool (eg, grasping, probing, pulling).

Another important factor is the geometrical constraints of the tool. Tool diameter and length determine how flexible the tool can be. If the tool is long and has a small diameter, then it is relatively easy to deflect. Thus, the greatest difficulty in designing tools for use in microenvironments is overcoming the tradeoff between rigidity and size. Stiffness is inversely proportional to the length, making the port design popular in some neurosurgical robots because it can reduce the length.[26]

Neurosurgery involves a microscopic field with minimal room to work, which creates challenges relating to instrument crowding, triangulation, and movement. The designs of robotic arms have assuaged the issue of triangulation and movement,[26] but crowding and workspace still add to the technical challenge of tight spots during surgery. Although surgeons have successfully performed dissections of superficial brain tumors,[27] robotic-assisted endoscopic surgery requires more research and technical improvements to comfortably access deep portions of the brain for everyday neurosurgical applications.

Motion

Manufacturers often describe surgical robots by the DoF in each articulating arm. DoF depend on the number of links in the system and the allowable directions in each motion. Six DoF allow a robot arm to move anywhere in the work envelope, but only 1 possible solution (joint angles) exists for each position in space. Thus, many robotic designs add redundancy — extra DoF — to allow multiple joint solutions/angles to reach the same position. Extra DoF are ideal in teleoperated surgeries because the surgeon has real-time control of each position; however, extra DoF in autonomous systems leave each desired position with multiple solutions, thus requiring extensive programming to optimize and coordinate motions.

One important factor of DoF is the amount of force delivered. The strength of the motor and mechanical advantage determine the applied force or force the motor can apply to maintain position; this is important when a surgeon wants to manipulate an object. Brakes are a way of increasing the force at which a motor can hold, but the applied force is still needed for manipulation. Including larger and more powerful motors in the system may sound like the solution, but the tool now creates a bottleneck in which the deflection and stiffness determine the applied force. Strength in DoF is another important factor, but its magnitude depends on the application. For example, manipulating portions of the brain does not require extensive applied forces, but manipulating bone or cartilage does.

Human–Robot Interactions

Haptic Feedback

A common natural mechanism that surgeons rely on is haptic feedback, or sense of touch, which can help determine how much force is being applied or provide information on the medium being manipulated. Proprioception, which is the sense of where one's connected extremities are in space, is another natural mechanism used during surgery. During minimally invasive and endoscopic surgery, long tools attenuate and distort the tactile sensation and proprioception of the surgeon.

Force Sensing

Telesurgery separates the direct connection between surgeon and patient, thus removing all haptic and proprioception feedback. Haptic feedback is a common concern in robotics because oftentimes the surgeon must know what forces are being applied to the workspace. This is particularly important in neurosurgery because delicate tissues can be permanently damaged by excessive force. Wagner et al[28] have shown that surgeons damage less tissue and apply minimal force to tissues when force feedback is received during robotic-assisted surgery. Thus, the topic of haptic feedback for robotics is an important area of research.

Force sensing for robotic applications is complicated in biomedical applications. Sterilization, MRI, size, electronics, and cost are factors that add to this complexity. Nevertheless, the minimally invasive field of neurosurgical robotics is a promising area of current research.

Some promising types of force feedback are in strain gauges and optical force measurements. For example, Yoneyama et al[29] developed a micromanipulator capable of providing clamp and tension feedback for deep-seated tumors through the use of strategically placed strain gauges. Doing so gives surgeons the ability to gather information on a tumor prior to resection. However, strain gauges are difficult to sterilize and have wires connecting them to other devices, causing researchers to pursue alternative ideas. Watanabe et al[30] developed a force-sensing device with a smaller probe diameter than the previous sensor capable of providing compression feedback by measuring the optical displacement of high elastic fiber. Optical displacement force is a promising application, and we expect this to become the future of force-sensing technology because endoscopic cameras are evolving and its potential for use in minimally invasive surgery is high.

Regardless of how force is measured, the main goal of such technology is to create a convincing virtual environment for surgeons. However, neurosurgery is potentially a few steps behind in haptic breakthroughs because of the microscopic requirements of the surgical environment.

Proprioception Feedback

Natural haptic feedback is the body's ability to determine the spatial location of our arms and hands without visual confirmation, and the loss of this sense contributes to the learning curve of telesurgery. Transferring our proprioception to a robotic arm is easier to imagine than it is to accomplish, which explains the limited research on this topic. However, it is an entertaining notion to consider because properly applying proprioceptive haptic feedback may provide the same "feel" as open surgery with minimally invasive procedures.

Calculating complex motions and training to operate robotic systems are highly dependent on the application of proprioception. Given enough time and training, a surgeon can gain a degree of proprioception when operating a robotic system. The time it takes to gain the skills to fluidly operate a robotic system is often referred to as the learning curve, which relates to the similarities of natural motions with robotic controls.

Kinematics

Robotic-assisted telesurgery can provide the surgeon with several advantages, such as comfort, accuracy, stamina, and dexterity. In addition, motion amplification and filtering can be included in robotic-assisted minimally invasive surgery. Because neurosurgery involves a microscopic field in which the surgeon must make accurate small incisions and resections, the use of motion filtering removes hand tremors from the surgeon by clever programming, thus allowing the surgeon to make smaller resections with larger applied motions. This, in turn, provides a factor of safety to the surgery.

Visualization

Visualization is the key component of successful haptic feedback and successful surgery. Several methods of visualization are available to surgeons, including CT, MRI, fluoroscopy, and endoscopic optics. Autonomous robotic assistance (eg, stereotactic applications) benefits from the use of CT and MRI because autonomous robots require a 3-D model of the workspace and presurgical programming. Master/slave or telesurgery applications benefit from endoscopic optics for real-time and perspective visualization during surgery and MRI and CT visualization for presurgical strategies.

Technological advancements have made endoscopy an attractive option for neurosurgeons, particularly robotic-assisted minimally invasive teleneurosurgery. Endoscopic optic cameras are useful in telesurgery because they can be flexible and have high resolution. However, telesurgery shares similar visualization challenges as endoscopic surgery, such as lens obstruction and blood clouding, and the approach to the workspace places limits on visualization and ease of manipulation.

Visualization is important for surgeon–workspace interaction. Because haptic feedback is limited, surgeons rely on visual feedback alone for telesurgery. Visual feedback is more useful than other feedback mechanisms and, thus, has received the most attention in surgery. Surgeons lose a degree of depth perception during operations by trying to process a 3-D environment from a 2-D image; this loss of perception can lengthen the duration of operating time. Therefore, current endoscopic designs include stereoscopic cameras. Some researchers have advocated stereoscopic over monoscopic surgeries,[31,32] but others question their efficacy.[33] Nevertheless, the topic is debatable as stereoscopic visualization does have potential advantages.

Microscopic visualization is important in neurosurgery and has potential in robotic surgery. Currently, NeuroArm is capable of microneurosurgery and has micro–end effectors for its tools.[34] However, not all systems are adaptable to microscopic visualization. Rather, integrating microsurgery into endoscopic robotic systems is more likely with the development of microendoscopy, but doing so may be difficult for minimally invasive systems because they may interfere with the view in the surgical field.

Augmented reality (AR) can provide advantages for visualizing surgical procedures. The concept of AR is to overlay artificial images from intraoperative CT scans or radiographs onto the current visual field. For example, AR can accentuate important but hidden anatomical structures and show the surgeon the position of lesions beneath tissue so that the lesions can be removed. Thus, adding AR technology to robotic systems is needed to help surgeons regain insight during surgery.

Training

A challenging issue with robotic-assisted surgery is the training of surgeons. Such training involves learning the basic kinematics of the robotic system. Training is an important factor and can occur in 2 different types of environments — virtual reality (VR) and deceased donor — and each has advantages and disadvantages.

In general, there are 2 types of VR: programmed VR and preoperative-preparation VR. Programmed VR is the first step in training and provides specific obstacles for the surgeon to practice so he or she gains anatomical experience prior to the actual surgery. One benefit of programmed VR training is its ability to provide tuned haptic feedback that a surgeon might encounter during surgery. Preoperative-preparation VR uses data from the patient (preferably from a high-resolution scan) to create a 3-D virtual representation of the surgical field that the surgeon then uses to rehearse the surgery and learn the anatomical features specific to the patient. The inclusion of haptic feedback in this type of VR may produce better emulation, but, to our knowledge, preoperative-preparation VR does not currently provide haptic feedback.

Surgeons can use robotic systems on deceased donors to rehearse potential surgeries prior to operating on patients. This type of training can also include a stereoscopic element to allow surgeons to learn and experience how the pseudo–3-D environment of robotic systems works, thus allowing extended proprioceptive feedback of the tools. Although the cost of deceased-donor training cost is higher than VR, deceased-donor training is still the best representation of the surgical field.

Future Directions

Several directions are possible for robotic-assisted minimally invasive surgery. In the future, robots may be completely autonomous, completely dependent, or even a hybrid of these 2 types of machines.

The notion of a completely autonomous robot is entertaining, but several complexities still exist. Treatment is not universal. Anatomy and medical history both differ from patient to patient. Currently, adjusting movement on demand is not yet possible, and the inability of robotic systems to make such on-demand adjustments makes troubleshooting or unexpected maneuvers an issue. Autonomous technology may be in the future, but strenuous work is needed to get there; thus, for the time being, autonomous robots are used for stereotactic assistance or equipment positioning alone. However, room for improvement still exits, including the addition of subroutines to current autonomous robotic systems, such as wound closing, clamping, and basic manipulation.

Completely dependent robotic-assisted surgery has become popular, and the future of dependent systems will rely on the miniaturization of robotic tools and the incorporation of curved endoscopic ports. The shortcomings of small, long parts relate to their flexibility, which limits how small each arm can be. However, future directions might include using several small robotic arms to assist 2 controlled hands to accommodate the limited forces that they can apply. For example, a system might include several robotic arms: the surgeon would control 2 of these small arms, and the other arms would be programmed to assist the surgeon. Nevertheless, once the technology is available, robotic-assisted endoscopic surgery is likely to become a major trend in neurosurgery.

Conclusions

The use of robotic systems in neurosurgery may help increase surgical accuracy and allow surgeons to perform more complicated operations. However, our current robotic technology is limited due in part to anatomical challenges, so other specialty areas have grown much faster than neurosurgery. Several technical challenges, including design issues and limited haptic feedback, have slowed down robotics in the field of neurosurgery, but researchers continue to work on creating a believable virtual environment that can replicate actual surgeries.

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