IN TOUCH WITH ROBOTICS: NEUROSURGERY FOR THE FUTURE

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THE INTRODUCTION OF multiple front-end technologies during the past quarter century has generated an emerging futurism for the discipline of neurological surgery. Driven primarily by synergistic developments in science and engineering, neurosurgery has always managed to harness the potential of the latest technical developments. Robotics represents one such technology. Progress in development of this technology has resulted in new uses for robotic devices in our discipline, which are accompanied by new potential dangers and inherent risks. The recent surge in robot-assisted interventions in other disciplines suggests that this technology may be considered one of a spectrum of frontier technologies poised to fuel the development of neurosurgery and consolidate the era of minimalism. On a more practical level, if the introduction of robotics in neurosurgery proves beneficial, neurosurgeons will need to become facile with this technology and learn to harness its potential so that the best surgical results may be achieved in the least invasive manner. This article reviews the role of robotic technology in the context of neurosurgery.

KEY WORDS: Computer-directed surgery, Neurosurgery, Robot, Robotic technology

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The discipline of neurosurgery has undergone seismic change during the past 50 years. Technological advances such as the operating microscope, modern neuroimaging techniques, endoscopic surgery, and computer-assisted surgery (CAS) were based on the principles of stereotaxy and supported by an explosion in computer technology. These advances have stimulated and augmented the concept of minimally invasive neurosurgery. Soon the scale of surgery will become so small that even the most skilled surgeon will reach the limit of his or her dexterity. New surgical paradigms will require improved precision that will be achievable only through a nexus of technologies that incorporate computer science, robotics, nanotechnology, biosensor technology, and machine intelligence.

Exposure to robots and robotic technology, whether via science fiction, the space program, or as used to retrieve artifacts from sunken ships, have made society grow accustomed to their existence, thereby increasing the likelihood of acceptance of robots for use in other endeavors. The economic advantages, increased precision, and improved quality of product persistently demonstrated by industrial robots stimulated the application of robots in the health sector. Although the first robot-assisted surgical intervention was performed in 1985 (39), the field of medical robotics, particularly robotics in neurosurgery, continues to emerge and has not reached critical mass. Inherent safety concerns and the observation that the growth of medical robotics seems to parallel that of CAS apparently have slowed the development of robotic technology in neurosurgery.

The incorporation of robotic technology in the neurosurgical operating room seems to be imminent, as surgical benefits have been quantified for recent robot-assisted interventions (2, 5, 12, 14, 22, 28, 30, 33, 38, 40, 41, 44, 50, 52, 58, 61, 66). In this review, we provide insight into the fundamentals of surgical robotic technology with emphasis on the development and status of robotics in neurosurgery, integration with current mainstream surgical technologies, current limitations, and technical challenges.

COMPUTER-ASSISTED VERSUS COMPUTER-DIRECTED SURGERY (NEUROROBOTIC SURGERY)

Although robotic technology may be envisaged for use in a wide range of surgical procedures, current applications have mainly concerned stereotaxy. With their precise, deliberate, and spatially encoded movements, robots may be considered instruments of stereotaxy. Therefore, computer-assisted neurosurgery may be regarded as a transitional technology to more precise robotic neurosurgery in the near future. Both modes of surgery are similar with respect to preoperative planning and registration, but they differ in key aspects during the intraoperative phase. In the preoperative planning phase, a robot will allow computer simulation sequences of robotic motions with a virtual haptic interface, allowing the surgeon to practice the operation before performing the procedure. The robotic system, unlike CAS, is motorized and may be independent of the surgeon with superior ability to constrain and work with surgical tools. The robot is only directly involved with the patient during the interventional phase of the procedure. The fundamental advantages of robotic-directed surgery over CAS are greater accuracy, precision, and sustained identical repetitive motions (31). Robots have superior three-dimensional (3-D) spatial accuracy, especially when linked to digitized image information. A significant improvement in manual dexterity is possible with a robotic interface. This allows the surgeon to operate through smaller corridors of access, to choose longer working distances without tiring easily, and to perform microsurgery on even smaller structures than currently possible. Furthermore, the surgeon's physiological tremor of $\sim 40\ \mu m$ can be reduced to $\sim 4\ \mu m$ by the use of a robotic interface (4). Because of their precision and accuracy, robots have the potential to produce more reproducible outcomes with smaller margins of error. *Table 1* lists the advantages of robotic surgery over CAS in more detail.

TABLE 1. Advantages of robotic surgery system over computer-assisted surgery[a]

Accurate and predictable, predefined and reprogrammable complex 3-D path
Both have accuracy and repeatability to position and orientate at a reprogrammable point, with robot accuracy higher
Ability for repetitive motions, for long periods
Moves to a location and then holds tools for long periods accurately, rigidly, and without tremor
Actively constrains tools to particular path or location, even against externally imposed forces, thus preventing vital organ damage
Responds and adapts quickly and automatically to sensor signals or to a change in commands
Ability for precise micromotions with prespecified microforces

[a] Modified from Davies B: A review of robotics in surgery. **Proc Inst Mech Eng [H]** 214:129–140, 2000 (19).

ROBOTS IN SURGERY

A surgical robot may be defined as: "A reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks" (Robot Institute of America, 1979 [67]). At its most basic level, a robot consists of the following components: Mechanical device consisting of a wheeled platform, arm, and/or other construction capable of interacting with its environment; sensors that receive information from both internal (robot) and external (environment) sources; and systems that assimilate and process the input data in the context of the device's current situation and instruct the robot to perform appropriate responsive actions. A robot is connected to a computer (controller), which is the "brain" that allows the robot to be networked to other systems for integration with other processes and robots. Many robots are robotic arms designed in various shapes and sizes. The arm is situated such that the end-effector ("hand") and sensors can perform the preprogrammed task. The robotic arm may resemble human arms with components such as shoulders, elbows, wrists, and even fingers. This design, which is based on human anthropometrics, allows the robot to be positioned in a variety of ways in the workspace. Each joint having 1 degree of freedom implies that a simple robotic arm with 3 degrees of freedom may move in three ways: left and right, forward and backward, and up and down. Most working robots have 6 degrees of freedom that are adequate to perform basic tasks through arbitrary positioning and orientation of the end-effector. The end-effector is connected to the robot's arm and ultimately performs the preprogrammed task; it may be a tool such as a probe, endoscope, or retractor. Sensors provide feedback so that the robot may safely perform the task. These sensors also relay spatial information back to the controller, informing the computer regarding of the exact location of the robot in the environment. The actuator is the engine that powers the sections between the joints to their desired positions. Most actuators are powered by hydraulics, air, and/or electricity.

To understand the potential impact of robotics in neurosurgery, it is important to understand the relevant key differences between humans and machines (*Table 2*). The main advantages of robots come from their ability to use abundant, detailed, quantitative information to perform accurate, repetitive motions and to operate in environments inhospitable or inaccessible to humans (especially through telesurgery and supervisory control). However, they have very limited decision-making and qualitative judgment ability. Conversely, humans are superior at integrating diverse sources of information, using qualitative data, and exercising judgment. Humans also have superior dexterity and robust hand–eye coordination, although at a limited scale, and most importantly an exquisite sensation of touch. These crucial differences in capabilities imply that current surgical robotic systems are restricted to basic tasks, with the surgeon providing detailed preoperative commands or exact move-for-move instructions to complete the preprogrammed task.

The current function of surgical robots is, therefore, to assist the surgeon under his or her supervision and to extend or enhance human skill rather than to replace the surgeon. These robotic systems enhance the practice of surgery by allowing the surgeon to operate at a very small scale (microsurgery) or through very limited access (minimally invasive surgery), to perform highly accurate and repeatable manipulation (stereotactic surgery), or to perform surgery with the use of large amounts of quantitative information (image-guided surgery). The versatility of robots means that these systems have multiple applications in the medical field.

TABLE 2. Differences between humans and robots[a]

Humans	Robots
Strengths	
Strong hand–eye coordination	*Good geometric accuracy*
Dexterous (at human scale)	*Stable and untiring with repeatability*
Flexible and adaptable	*Designed for wide range of scales, motion scaling with potential future applications for micro- and nanosurgery*
Able to use qualitative information	*Integrates extensive and diverse information*
Good judgment	*Uses diverse sensors (chemical, force, acoustic, etc.) in control*
Limitations	
Limited dexterity outside natural state	*Limited dexterity and hand–eye coordination*
Prone to tremor and fatigue	*Poor qualitative decision-making ability*
Limited ability to use quantitative information	*Limited to relatively simple tasks*
Limited sterility and prone to error	*Large operating room space requirement, expensive, technology in flux*

[a] Adapted from Howe RD, Matsuoka Y: Robotics for surgery. **Annu Rev Biomed Eng** 1:211–240, 1999 (34).

Technical Classifications

From a technological viewpoint, use of robotics in surgical applications comprises passive or active effector systems. A passive mechanism is one in which the surgeon provides the physical energy to drive the surgical tool; the robot, once positioned, acts as a means of holding fixtures at a predestined location to facilitate the precise acquisition of the preoperatively defined target. In this way, the "powered off" surgical robot, locked into position, can be used in a safe manner. The earliest application of a surgical robot was used in this manner (39).

In active robotic systems, a powered robot actively interacts with a patient, therefore allowing more complex motion to be accomplished. This robotic system has greater autonomy and the surgeon has the ability to monitor the entire process and intervene as necessary. An intrinsically safe design is a mechanism that has physically restricted motion so that all possible motions are safe; however, software problems or incorrect use may override an intrinsically safe mechanism (13).

Interaction Classifications

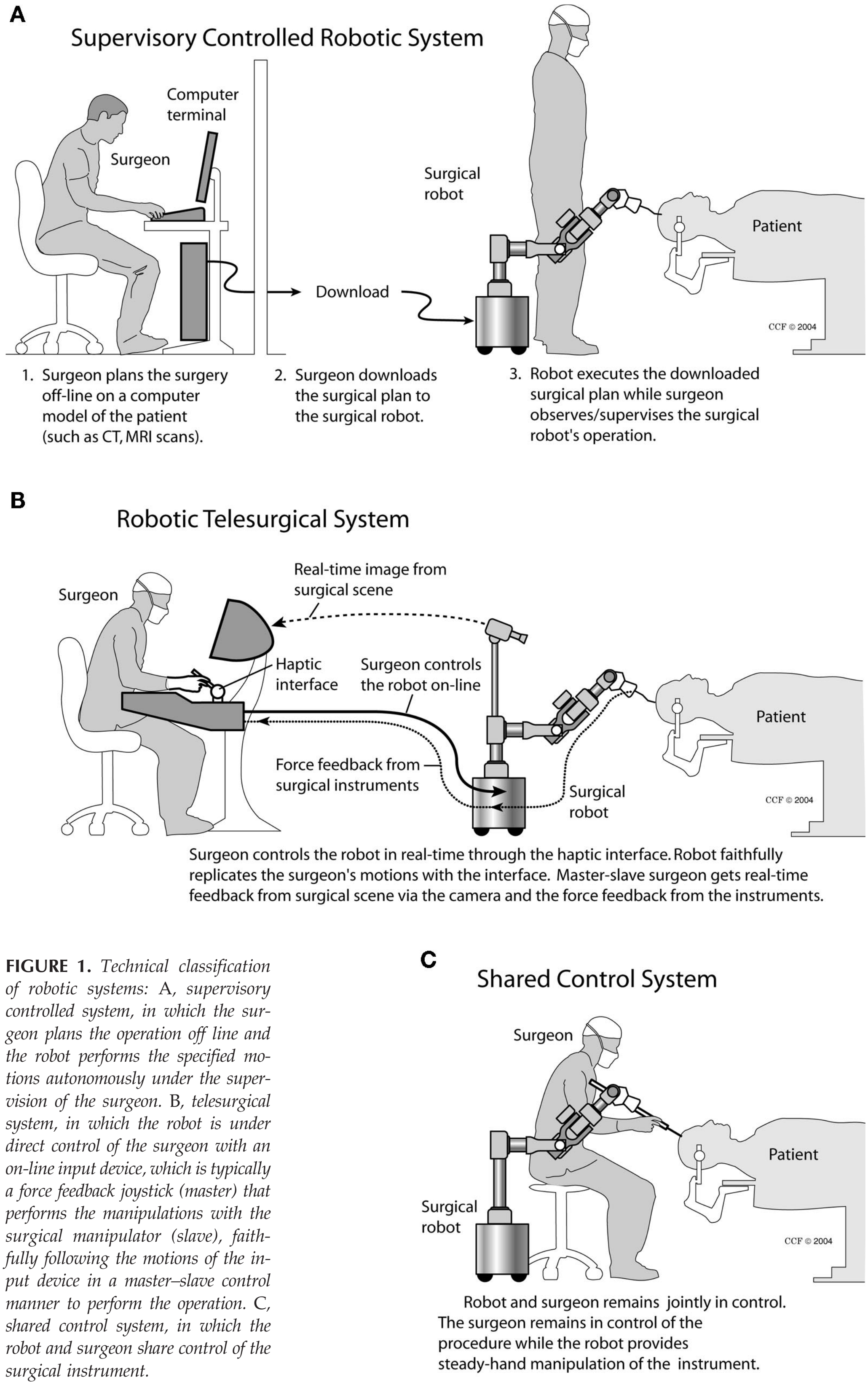
Surgical robots can be classified into three broad categories on the basis of how the surgeon interacts with them. In supervisory-controlled systems, the surgeon plans the operation off line and implicitly or explicitly specifies the motions the robot must follow to perform the operation (*Fig. 1A*). The robot then performs the specified motions autonomously under the supervision of the surgeon.

In telesurgical systems, the surgical manipulator is under direct control of the surgeon with the surgical tools in the form of a robotic manipulator (*Fig. 1B*). With an on-line input device that is typically a force feedback joystick (master), the surgeon performs the surgical manipulations, and the surgical manipulator ("slave") faithfully follows the motions of the input device in a master–slave control manner to perform the operation (16, 17, 56).

In shared-control systems, the surgeon and robot share control of the surgical instrument (*Fig. 1C*) (3, 58). In these synergistic systems, the surgeon remains in control of the procedure and the robot provides steady-hand manipulation of the instrument.

Dexterity Enhancers

Given the current limitations of robotic technology, the main focus of medical robotics technology development has been integrating the abilities of human and robot to enhance the surgeon's manipulative capabilities at the microscopic scale and improving the access to areas of the brain that are traditionally difficult to access, rather than developing robotic systems that would be aimed to replace the surgeon (*Fig. 2*). Technology designed to increase the precision of the surgeon's hands to the level enabled by microscopy is termed *dexterity enhancement*. This can be achieved with a telesurgical or shared-controlled surgical



1. Surgeon plans the surgery off-line on a computer model of the patient (such as CT, MRI scans).
2. Surgeon downloads the surgical plan to the surgical robot.
3. Robot executes the downloaded surgical plan while surgeon observes/supervises the surgical robot's operation.

Surgeon controls the robot in real-time through the haptic interface. Robot faithfully replicates the surgeon's motions with the interface. Master-slave surgeon gets real-time feedback from surgical scene via the camera and the force feedback from the instruments.

Robot and surgeon remains jointly in control. The surgeon remains in control of the procedure while the robot provides steady-hand manipulation of the instrument.

FIGURE 1. *Technical classification of robotic systems:* A, *supervisory controlled system, in which the surgeon plans the operation off line and the robot performs the specified motions autonomously under the supervision of the surgeon.* B, *telesurgical system, in which the robot is under direct control of the surgeon with an on-line input device, which is typically a force feedback joystick (master) that performs the manipulations with the surgical manipulator (slave), faithfully following the motions of the input device in a master–slave control manner to perform the operation.* C, *shared control system, in which the robot and surgeon share control of the surgical instrument.*

robotic system. A computer-controlled mechanism is placed between the surgeon's hand and the tip of the surgical instrument. This allows the surgeon's motions to be relayed to a computer processor, which digitizes his or her hand motions. The surgeon's hand motions in a digital format are then precisely manipulated and filtered by the system's software to remove surgical tremor and to scale down gross macroscopic movements to a microscopic scale (scale of motion) inside the patient, thus enhancing dexterity.

ROBOTS IN OTHER SURGICAL DICIPLINES

Intracranial neurosurgical procedures were the focus of the first robotic systems, partly because a high degree of precision was required for localization and manipulation within the brain and because the cranial anatomy provided relatively fixed landmarks. Use of medical robots then expanded to other fields and has been applied in several other surgical disciplines. Davies (19) was the first to use an active motion robot for soft tissue surgery in early 1991; this was the forerunner to the Probot, which is used currently for transurethral resection of the prostate (47). In late 1991, Robodoc (Integrated Surgical Systems, Davis, CA) (5) underwent clinical evaluation in humans. The Robodoc system prepares the proximal femur to accept an uncemented total hip prosthesis. The cavity it creates is 10 times more accurate than that achieved via manual reaming (56).

In 1994, the United States Food and Drug Administration approved the first robot for clinical use in the abdo-

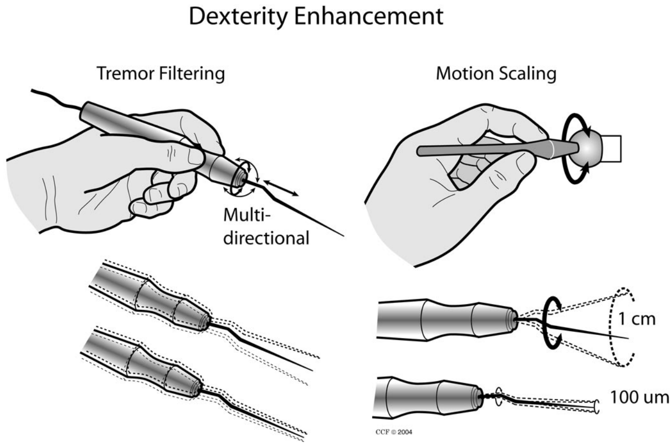


FIGURE 2. *Dexterity enhancement: The surgeon's hand motions are digitized, precisely manipulated, and filtered to remove physiological tremor and/or to scale down gross macroscopic movements to a microscopic scale (motion scaling) inside the patient, thus enhancing dexterity.*

men. Modified from a robotic arm used by NASA in the space program, the Automated Endoscopic System for Optimal Positioning (AESOP) (Intuitive Surgical, Inc., Sunnyvale, CA) was developed to hold a laparoscopic camera. A voice-activated version of AESOP was developed later. AESOP has facilitated solo-surgeon laparoscopic procedures in general surgery (24).

In 1994, the first telesurgical robot was developed by SRI International, Inc. (Menlo Park, CA) (32). It was a demonstration developed under a contract for the United States Defense Advanced Research Projects Agency to demonstrate the feasibility of remote telesurgery. The initial system was developed for open abdominal surgery. Subsequently, a laparoscopic version was designed.

The Zeus (Intuitive Surgical, Inc.) (38, 50) and daVinci (Intuitive Surgical, Inc.) (14, 44) robotic systems have been successfully used in cardiac surgery. Recently, the United States Food and Drug Administration approved the Zeus robotic system for limited clinical application in chest and abdominal surgery and the daVinci system for mitral valve repair surgery.

THE STATUS OF ROBOTS IN NEUROSURGERY

A brief review of pioneering developments in intracranial localization is appropriate at this point before the developments in robotic neurosurgery are discussed. Advancement to the concept of intracranial navigation began with initial stereotaxy, i.e., point localization, and progressed to the concept of volume stereotaxy, opening a new era for neurosurgeons to work through narrow but safe functional corridors and gain access to deep lesions (37). Three concurrent technological advances established a foundation for the transition from frame-based to frameless stereotaxy: improved spatial fidelity of volume imaging data, rapidly expanding computational power, and the development of accurate 3-D digitizers (36, 62). This gave rise to a number of different concepts related to digitizers and image display (6, 20, 27, 48, 54). The consolidation of these technologies resulted in the commercial development of image guidance systems that have widely influenced most aspects of current neurosurgical practice.

Robotization of neurosurgical procedures was the next logical step. A large technology base existed in robotic research, derived mainly from experience in the industrial sector. This facilitated the transformation of industrial robots to medical robots. Kelly (36), who first described the application of CAS in neurosurgery, introduced a Cartesian robot for positioning the head within the Compass stereotactic head frame (Compass International, Rochester, MN) (35). The integration of robotic technology into the neurosurgical operating room advanced significantly with the adaptation of industrial robots to perform simple stereotactic tasks. The first recorded medical application of a robot occurred in 1985, when Kwoh et al. (39) used a modified Puma 560 industrial robot (Advance Research & Robotics, Oxford, CT) to define the trajectory of a frame-based brain biopsy. After input of the x-y coordinates of an image-identified intracranial lesion, the robotic effector arm with the probe holder moved to the defined location. When the probe holder reached the target coordinates, the robot was locked in position and the power removed, making it effectively a passive system. The surgeon then used the probe as a guide for drilling the bone and biopsy of the lesion. Unfortunately, safety protocols dictated that industrial robots were required to operate inside a cage, away from people. Consequently, this work was discontinued. Drake et al. (21) later used a modified industrial robot to resect deep benign astrocytomas in a small series of patients.

Development of robotic instrumentation specifically designed for operative tasks was the focus of both the Grenoble team led by Benabid et al. (7, 9–11) and the Minerva project in Lausanne (26). Minerva was designed to meet exacting specifications incorporating safety, geometry, and to perform single dimensional incursions into the brain while the patient was within a computed tomography system that continuously provided real-time imaging data to the robot. This project was discontinued in 1993.

The merging of the roboticized microscope holder developed in Grenoble (Dee-Med, Grenoble, France) with frameless co-registration methodology produced the SurgiScope stereotactic system (Elektra AB, Stockholm, Sweden) (10, 42, 51). The MKM microscope system (Carl Zeiss, Inc., Oberkochen, Germany) (49, 63) and the telerobotic system described by Giorgi et al. (25) are similar robotic devices.

In 1990, Adler et al. (1) described an innovative approach to radiosurgery. They used a mechanically precise robot delivery system to manipulate a lightweight X-band linear accelerator as it delivered closed-cranium (or body) radiation of a target volume identified with preoperative imaging. This system has been successfully integrated into standard clinical neurosurgical practice for the treatment of central nervous system tumors. Unlike frame-based systems, the CyberKnife (Accuray, Inc., Sunnyvale, CA) is noninvasive and compensates for limited movement of the target.

NeuroMate (Integrated Surgical Systems) is the first United States Food and Drug Administration-approved, commercially available, image-guided, robotic-assisted system used for stereotactic procedures in neurosurgery. This six-axis robot evolved from the work of Benabid et al. (7) at Grenoble University. The current version has been modified from the original design to incorporate specific stereotactic requirements and to improve safety issues (8). The application accuracy of this device is comparable to frame-based or infrared tracking localized systems (41) and has been successfully used in a frameless mode for movement disorder surgery (61).

As the brain is best visualized with magnetic resonance imaging (MRI), robotic systems compatible to work in this environment have been developed. Rather than modifying a preexisting industrial robot, Masamune et al. (43) designed an MRI-compatible robot based on safety and compactness at the University of Tokyo.

Recent, preliminary experience with a robot-assisted, navigation-guided neuroendoscope (66) and robot-assisted thoracoscopic resection of a benign mediastinal tumor (52) has been reported. The use of teleoperated micromanipulators in a master-slave relationship has been demonstrated in laboratory settings (28, 33, 40). The NeuRobot telerobotic micromanipulator has been used successfully to perform an endoscopic third ventriculostomy and dissection of the sylvian fissure in a cadaveric specimen (33) and more recently has been used in a limited fashion in the clinical setting of tumor resection (28).

TECHNICAL AND IMPLEMENTATION CHALLENGES

When an intracranial lesion is encountered for the first time, a surgeon attempts to understand its identity better by accruing information with regard to its size, location, boundaries, and neighboring structures. Its identity usually is deduced from clinical examination, preoperative neuroimaging, and in-depth knowledge of 3-D anatomy. These factors, coupled with surgical experience, manual dexterity, and hand–eye coordination determine the intraoperative actions of the surgeon. For robotic systems to perform this form of intellectual functioning autonomously in a complex 3-D environment, they must use quantitative reasoning and broad-based sensory integration derived from multiple sources (e.g., stereoscopic vision, kinesthesia). This is not possible with existing technology, however, as it requires a quantum leap in allied translational disciplines such as computer sciences, nanotechnology, biosensor technology, machine intelligence, and robotics. For this reason, robots are unlikely to replace surgeons in the foreseeable future.

Despite their obvious benefits, surgical robotic systems are still a long way from wide acceptance and use in neurosurgical practice. The high cost of the currently available systems, poor human-to-machine interface, lack of portability, undesirable ergonomics, and most importantly, their isolation from clinical reality limits robot integration into mainstream neurosurgical practice. In this section, we discuss the technical research challenges and advanced computer paradigms that will improve technology of current surgical robotic systems.

Human–Machine Interface Issues and Machine Haptics

There are a number of human–machine interface problems with current medical robotic systems that require development of interface technologies to match and complement human abilities to the surgical tasks (59). Existing manual instruments for minimally invasive surgery significantly reduce dexterity and impair sensation. They also limit force sensing with near complete removal of tactile sensation. Current robotic telesurgical systems are targeted at improving the dexterity of surgical manipulation by increasing the motion degrees-of-freedom available in instruments and providing user interfaces that improve hand–eye coordination.

Despite being precise and tremor-free in the execution of tasks, current surgical robotic systems lack one crucial attribute that surgeons prize: the delicate sense of touch. Be it the splitting of a sulcus or suturing, tactile sensation and force feedback is key to the success of these complex surgical tasks. Important tactile display modalities that need incorporation into future robotic systems include vibrotactile feedback and thermal sensors. Some studies have explored improving force and tactile sensation in telesurgical and other medical robotic systems (15, 29). For force feedback, improvements must be made in sensor technology, e.g., scaling down the size of force sensors to fit at the tip of surgical instruments yet maintaining high precision and low measurement noise. For efficient tactile feedback, small sensor arrays are available that can easily fit on surgical instruments, but the currently available displays are quite bulky. The new compliant tactile display technology that uses hybrid pneumatic/electric actuation promises significant improvements (45). There remains significant room for improving dexterity enhancement with surgical robotic tools. Experiments that analyzed the task completion times of surgeons performing point-to-point or basic manipulation tasks (not outcomes) have demonstrated that robotic telesurgical tools is still far from reproducing human manual dexterity with conventional surgical instruments (12, 22).

3-D spatial navigation, planning, and visual-spatial coordination form another set of major problems in robotic surgery, as they do in image-guided surgery. This set of human–machine interface problems is the result of complex and unfamiliar spatial transformations in image-guided surgery involving the surgeon's visual and haptic perception. Solutions to these problems require design of intuitive interfaces for use during surgical manipulation, especially for robotic surgery, and development of training strategies and tools to teach surgeons to interpret, understand, and handle the complex spatial interface. Use of virtual reality training simulators with haptic feedback provides a promising paradigm to teach these complex spatial cognitive skills (55, 60).

Soft Tissue Surgery and Deformability

In the realm of soft tissue surgery, robots must adapt to the deformability and mobility of the operated brain, and other soft tissue. Therefore, undue reliance of a surgical plan based exclusively on preoperative data acquisition is unsatisfactory. The complex behavior of soft tissues may be accurately determined via indentation, imaging, boundary condition methods, and mathematical modeling. There are two major approaches to address this problem.

The first approach is to use interventional imaging systems in conjunction with surgical robots. In this paradigm, a preoperative plan is constructed with high-resolution preoperative images and downloaded to the surgical robot in the operating room. The operation is performed within an interventional imaging system that acquires near- or real-time images, processes them, identifies the tissue deformations, and subsequently modifies the surgical plan on line, taking into account the changing surgical scenario as a result of soft tissue deformations. The most promising interventional imaging systems for intraoperational robotic assistance are MRI, computed tomography, and ultrasound imaging. The main difficulty with MRI and computed tomography relates to compatibility of the surgical robot with the imaging system. For example, a robot that will be used for performing robotic surgery inside an interventional MRI system must be made of materials that are not affected by the large magnetic gradients, and it should not interfere with operation of the MRI system or reduce image quality (18). This poses significant challenges in the choice of structural materials, actuators, and sensors and the design of the size and location of the system (23). Robotic image-guided surgery under ultrasound guidance is attracting attention because of the relatively low cost and wide availability of these systems. However, the low image resolution of ultrasound systems has proved to be a formidable challenge.

The second approach to handle soft tissue deformations during robotic surgery is to model and estimate induced soft tissue deformations during simulated surgical manipulation and compensate for its effects during the construction of the surgical plan. The major challenge in this approach is the prediction of the mechanical behavior of brain tissue, especially as the biomechanical properties are difficult to predict and highly variable under intraoperative conditions.

A technological spin-off from the NASA smart probe project is the development of multimodality stereotactic brain tissue identification by use of advanced information technology such as neural networking (2). The probe uses multiple microsensors, such as optical spectroscopy, microelectrode recordings, micro-blood flow dynamics, and microendoscopy to gather large amounts of data regarding the tissue at the probes tip in real time, thereby determining the nature of the tissue.

Safety

Safety is of paramount concern with robotic surgery and requires that rigorous, mandatory preclinical testing be undertaken before clinical application. Two major concerns of safety in medical robotic systems are the potential hazards to the patient as a result of failure and unintended actions by the robot and the safety of the surgical team that occupies the space around the patient and the robot. Although there are no universally accepted techniques to guarantee system safety under all circumstances, there are several general approaches for achieving hardware safety (34, 46).

Redundancy in kinematics and sensors is a very common technique used in surgical robots to improve system safety. This methodology is very effective in detecting and recovering from partial system failures, and has the potential to perform consistency checks to evaluate the integrity of the hardware. However, it should be noted that redundancy also increases hardware and software complexity, which increases fragility of the system overall and makes the design more costly (57).

Another common approach to improve safety of surgical robotic systems is to limit the size of the workspace of the robot to avoid potential unintended damage to areas outside the point of operation, use less powerful actuators, and combine active and passive mechanisms in the robot design (30, 53). There are two approaches to limiting the robot workspace. Either the surgeon moves the tool and the robot prevents motion outside the planned workspace, or, as with the Robodoc hip replacement system, the robot moves the cutting tool autonomously and the surgeon monitors the progress. Current clinical trials from Europe indicate clinician acceptance of this autonomous mode (5). As medical robotic use increases, surgeons will grow more accustomed to autonomously controlled robotic systems. Another important concern in surgical robotic system safety is sterilization. This is usually achieved by covering the entire surgical robot, with the exception of the surgical end-effector, with sterile drapes. The surgical end-effector, which is the part that is used on the patient, is sterile and reusable.

FUTURE SURGICAL ROBOTS

Despite a half-century of advancements in robotic technology, the capabilities of current systems remain limited. The mechanical robots of popular culture, although built to look, act, and emote like humans, are much different from contemporary surgical robotic systems in appearance and behavior. Robotic systems still have great difficulty identifying objects on the basis of visual appearance or feel and they handle objects clumsily, so they are far from ready to perform complex tasks such as surgery on the brain autonomously (other than as extensions of stereotactic surgery).

Almost all robots are preprogrammed by people and will only perform programmed tasks. In the future, it is likely that controllers with artificial intelligence (AI) will allow robots to "think" on their own or even program themselves, thereby making them more self-reliant and independent. No computer has gained the level of AI that comes close to simulating complex human behavior and thinking. The highest form of AI to date was demonstrated recently when the Deep Blue supercomputer (International Business Machines Corp.) beat the world chess champion, Gary Kasparov, in 1997.

For surgical robots to gain acceptance by neurosurgeons, they must possess qualities that will enhance the surgeon's manipulative capabilities and do so in a robust, user-friendly manner that is neither obstructive nor restrictive. In this section, we review some advanced technological paradigms that will provide the foundation for future surgical robotic systems to interact with surgeons in a seamless manner.

Machine/AI and Surgical Robots

AI has been one of the most controversial domains of inquiry in computer science since it was first proposed in the 1950s. Defined as "the scientific understanding of the mechanisms underlying thought and intelligent behavior and their embodiment in machines" (American Association for Artificial Intelligence [68]), AI has, unbeknownst to many, become part of our daily lives. AI integral to a swath of industries, e.g., assisting engineers to create better jet engines, boosting productivity through the use of monitoring equipment and signaling when preventive maintenance is needed, and assisting the Pentagon in coordinating its immense logistic operations. In the biotechnology sector, AI has been used to gain new insight into the human genome. Improvement of existing machine/AI applications will contribute to improvements in current surgical robot systems.

Artificial Sensory Modalities

For meaningful interaction between the robot and surgeon, perceptual abilities should overlap so that the each has an idea of the sensations and responses of the other. Under ideal circumstances, natural language processing will allow people to interact with computers without additional specialized knowledge, but this has proved difficult thus far. Although rudimentary translation systems are available, they are far less capable than human translators. Voice recognition systems that convert spoken sounds to written words are currently available, although these systems do not understand what they have written.

Two-dimensional inputs to the human eye are rendered in 3-D and interpreted by the brain. To achieve this function artificially by use of computer vision, the computer must gain information regarding the spatial properties of the environment, i.e., shape, motion, distances, and angles. These are measurable properties that can only be obtained as images change with time. Therefore, either multiple views from the scene are needed, or the viewer's perspective must change. Only then can a 3-D representation be created. With current computer vision, it is only possible to infer and understand 3-D information from images in a limited fashion that is far inferior to human vision. Assimilation and sequential compilation of multiple external sensory sources eventually will transform current rudimentary robotic systems from accurately programmed sequences of motions in a structured environment to dynamic behaviors planned in response to the external world.

Artificial Thought Processing

Expert Systems and Heuristic Planning

Expert systems are computer applications designed to replace and/or aid humans by performing tasks that would otherwise be performed by a human expert (e.g., financial forecasts, diagnosis of human illnesses). In this computational model, a "knowledge engineer" interviews experts in various domains and attempts to embody their knowledge in a computer program for performing each task. Heuristic planning uses commonsense rules drawn from experience to solve problems, in contrast to algorithmic programming, which is based on mathematical models. These programs are self-learning and their performance improves with experience. Most expert systems use heuristics.

Artificial Neural Networks

One of the most active areas of AI is neural networks. An artificial neural network is an information-processing paradigm conceived to process information similar to the densely interconnected parallel structure of the mammalian brain. An artificial neural network is simply a collection of mathematical models that mimic some of the observed properties in biological nervous systems and possess analogous adaptive biological learning. The information processing system is composed of large numbers of highly interconnected processing elements that are analogous to neurons and are tied together with weighted connections that are analogous to synapses. Similar to biological systems, learning typically occurs by example through training or exposure to a correct set of input/output data wherein the training algorithm autonomously adjusts the connection weights (synapses). These connection weights store the knowledge necessary to solve specific problems. Neural networks have become the standard for detecting credit card fraud in the financial sector.

The advantage of artificial neural networks is their resistance against distortions to the input data and their capabilities of learning and problem solving capabilities for conventional technologies. There is developing interest in how neural network research and neurophysiology can merge; a field called *computational neuroscience* has been conceived from both disciplines.

Fuzzy Logic

Another computational paradigm of thought processing is fuzzy logic, which uses a problem-solving control system methodology that provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing information. Fuzzy logic , which was introduced in 1960s

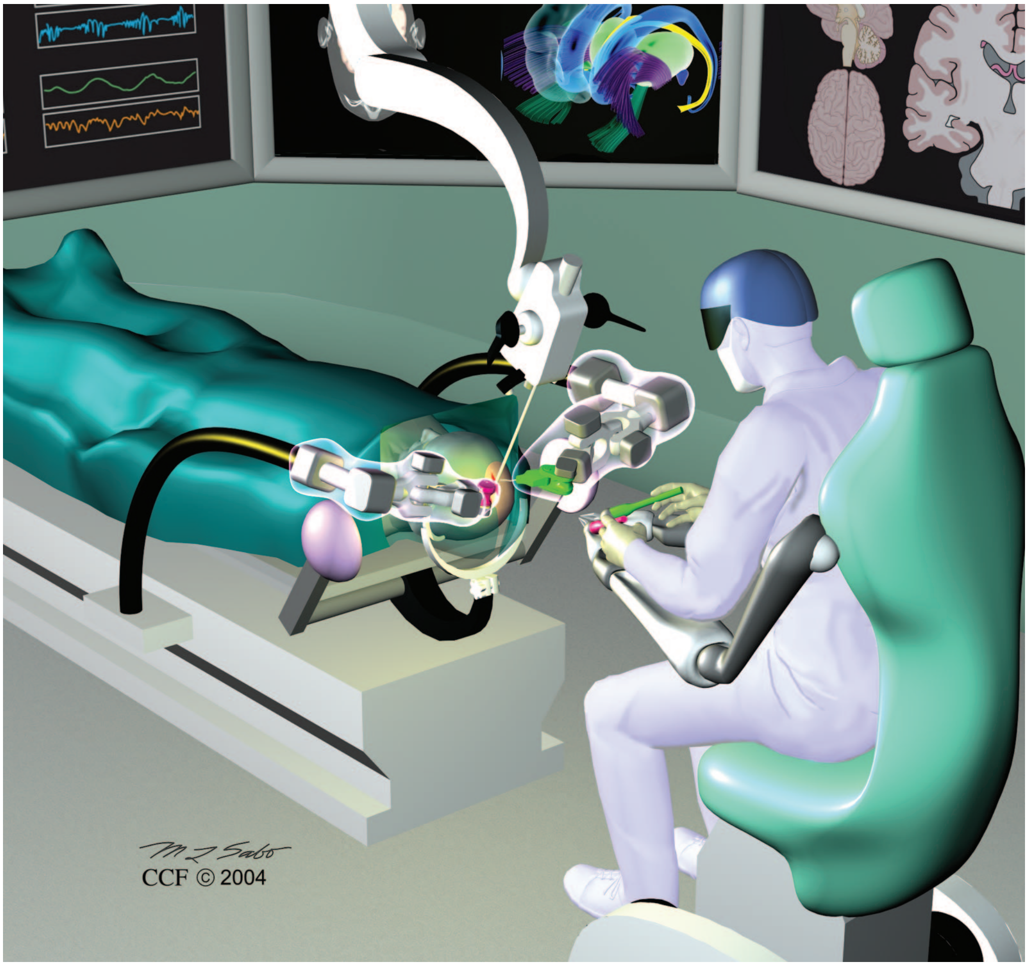


FIGURE 3. *Brain operating room and surgical robots in the near future. The surgeon, wearing a lightweight head-mounted visor with virtual retinal display technology, sits in a surgical cockpit, with capabilities of dexterity enhancement. An operating table, modular in design, incorporates rigid head fixation, intraoperative MRI, and a surgical robot with two end-effectors. Surgical visualization instruments (microscope and endoscope) will be coupled but optically delinked, with stereoscopic magnified images of the operative field integrated and fused with the multiple real-time image data sets defining the anatomic and functional substrates as appropriate.*

(64), incorporates a unique type of rule-based mathematical modeling and uses the "if x and y, then z" approach to solving problems (65) with a superset of conventional Boolean logic that has been designed to handle partial truth. It provides a framework to perform computation and mathematically represent the vague and imprecise nature of rules and information expressed with natural language, and it handles ambiguous and noisy information to mimic the way a human makes decisions.

CONCLUSION

Despite its debut more than 15 years ago, medical robotic technology has yet to gain prominence in neurosurgery. Achievement of this goal is probably a matter of time. We look forward to the development of MRI-compatible robotic devices that will have ambidextrous capabilities with persistence (i.e., ability to pick up where the surgeon has left off), multiple degrees of freedom, high bandwidth, and kinesthetic feedback yet are robust and user-friendly devices. Robotics will result in improved surgical techniques and facilitate the development of new procedures that could not be performed without the aid of this new class of tools. Undoubtedly, robotic technology is set to transform future neurosurgical practice (*Fig. 3*).

Convincing neurosurgeons and patients regarding robot safety may prove to be the biggest challenge to their implementation. It seems that robots will initially be more acceptable to the surgeon if the physician is in control of the entire surgical procedure, with the robot acting primarily as a dexterity enhancer (robot-assisted procedure). As robotic techniques become more integrated into practice, neurosurgeons should become familiar with this new interdisciplinary field termed *neurorobotics* (i.e., robotics applied to neurosurgery). Awareness of this technology is mandatory if we are to have a solid working foundation to handle the current and future needs of neurosurgical practice.

The integration of disciplines such as information technology, robotics, machine intelligence, nanotechnology, and sophisticated computational networking may revolutionize contemporary neurosurgical practice, thereby generating many potential new clinical applications. To ensure the broad application of robots to medicine and neurosurgery, a new era of collaboration and cooperation between surgeons and robotics scientists is necessary to drive this technological *tour de force*. However, factors such as cost and safety concerns undoubtedly will affect the incorporation of robotics into conventional neurosurgical practice. It will become imperative that residents and neurosurgeons become familiar with this form of technology so they can incorporate it into their future surgical armamentarium and, it is hoped, improve the quality of patient care. Because the general abilities of a robot and surgeon are dissimilar yet complementary, great synergy may be generated by combining the two with potential benefit to humankind, medicine, and neurosurgery.

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COMMENTS

The authors describe the basis of surgical robotics, previous experience with clinical robotics, and directions for development of future robotic applications in neurosurgery. They provide a basic review of robotic terminology and concepts, which are important for modern neurosurgeons to understand. Use of robotics in neurosurgery is not simply a passing fad; however, the correct applications must be found for the concepts outlined in this article to gain practical acceptance. Robotics in neurosurgery has developed on a convergent evolutionary path with computer-assisted surgery; the result will be the merging of these two technologies. Image guidance, coupled with the scaling and dexterity-enhancing properties of surgical robotics, will provide for a new era of minimally invasive neurosurgery. Robots used in this manner will not replace neurosurgeons in the operating room, but they will allow us to see and work in places that once required large exposures. Flexible endoscopes, end-effectors with multiple degrees of freedom, and stereotactic imaging techniques will allow us to see and work in deep locations and around corners, limiting patient morbidity. These concepts are beginning to become reality. Nathoo et al. provide a review of the status of neurosurgical robotics, but we have a long way to go. After the theoretical ideas are addressed, widespread acceptance will follow only when the practical concerns of reduced cost, ease of use, and improved clinical outcome are realized.

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Mirroring general surgery, a number of recent publications suggest growing interest among neurosurgeons in the burgeoning field of robotics. Nathoo et al. provide a relatively thorough overview of the robotic surgical field, which adds further to the topical literature. Having personally dedicated my professional career to a specific application of operative robotics, image-guided robotic radiosurgery, I am by nature an enthusiast for this emerging field. However, I have also experienced first-hand the economic realities that enable new surgical technologies to be developed. Although I agree that it might be feasible and even advantageous to redesign specific high-volume procedures (e.g., in the spine or deep brain stimulation) around a dedicated robotic tool, most of the recent emphasis in the neurosurgical robotics literature has been on conceptualizing a general-purpose robot for performing microsurgery. Despite the theoretical advantages of operating under robotic control or with robotic assistance, I remain skeptical that these putative benefits are currently great enough that companies will make the needed investment. Consequently, I think that for the foreseeable future, much of the enthusiasm for microsurgical robots in neurosurgery will remain within the realm of academic speculation.

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Nathoo et al. continue their series of reviews of robotics for neurosurgeons. All of us, especially neurosurgeons, love our machines. We want the newest technological toys in our operating rooms to enable us to perform our art faster, better, and safer. We readily embrace technology that extends our senses, improves our motor control, and speeds up the procedure. Why, then, have robots made so little impact in surgery in general and in neurosurgery in particular? The answer lies in *Table 7* in the article: there is a risk-to-benefit ratio, and currently the risks are simply too large to invest in expensive, bulky equipment that performs a limited number of rather simple tasks and has poor decision-making capability.

This limited capability hampers progress in this field of technology. Far more information must be supplied before robots can dramatically evaluate their environment. There is a very good reason why industrial robots are caged and humans must stay out of their working area: there is no feedback to these robots that would allow them to stop and prevent an injury should a human enter their work space. Artificial intelligence remains quite limited. Software "glitches" and the inability to correct errors, whether human or robotic in origin, means very slow acceptance of technology until these problems are corrected. Supervisory controlled robotics systems or robotic telesurgery systems will have a place in the neurosurgery technology armamentarium in the distant future. Before that can be accomplished, it must be proved that the precision elements that provide the strengths related to the use of robots have the safety and efficacy necessary to perform surgical procedures. A neurosurgery chairman once said that a monkey can be trained to perform the mechanics required for neurosurgery. It was pointed out later, however, that a human being with a great deal of intelligence, insight, and compassion is required to properly apply those mechanics when, where, and how they are needed.

People always have had a love/hate relationship with robots. This psychological barrier must be overcome. Science fiction has presented robots as both monsters and saviors. Classic science fiction movies such as *Forbidden Planet*, *The Day the Earth Stood Still*, *The Terminator*, and *Star Wars* play into our emotions regarding robots. Few surgeons and even fewer patients like the idea of autonomously controlled robotics systems performing potentially life-and-death procedures. I am not willing to accept that robots could or should "think" on their own or even program themselves. If one thinks of the personal computer, it is obvious that computers have a long way to go. Although IBM's Deep Blue supercomputer was able to beat world chess champion Gary Kasparov, Deep Blue does not always win, and it does not do so by any insight or innovation in the game of chess; it wins simply by manual calculation of the odds through possible steps into the future. Computer-assisted surgery has dramatically improved the practice of stereotactic and functional neurosurgery. However, the neurosurgeon must be the master of technology, as subtle errors can be introduced into stereotactic neurosurgical procedures extremely easily. The correction of some errors may require a little bit of common sense, but others require considerable experience and insight, e.g., the realization that a calculated target or trajectory is incorrect. If robots are ever allowed to "think for themselves," it is hoped that the programming will incorporate Isaac Asimov's three laws of robotics: 1) a robot may not injure a human being, or, through inaction, allow a human being to become harmed; 2) a robot must obey the orders given it by human beings, except where such orders would conflict with the first law; and 3) a robot must protect its own existence as long as such protection does not conflict with the first or second laws. A recently released film, *I, Robot*, incorporates a number of Asimov's ideas but is a story that is foreign to his writings. The plot involves program glitches that allow these laws to be ignored. I found myself sympathizing with the detective played by Will Smith. Who distrusts robots? As a police officer, he instructed a robot to save a child and sacrifice himself. The robot, calculating the probability of success, "chose" to save Smith's life against his instructions. I, too, will use robots but will never truly trust them. The problem is that robots will act based on their programming and observations, not on my experience and insight. Fuzzy logic is a poor match for the brain of an experienced neurosurgeon.

I agree with the authors that surgical robotic systems are a long distance from wide acceptance and use in neurosurgical practice. Many problems must be overcome before some of the simpler master-slave interactions can be perfected. We are much further away from allowing independent action under supervision or even shared control. The authors provide a reality check to the enthusiasm generally expressed for robotics.

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Nathoo et al. provide an overview of neurosurgical robotics and speculate regarding future developments in the field. We agree with the authors that the possibilities offered by robots make their incorporation into the neurosurgical operating room inevitable. However, this article overstates the ability of current robotic systems in many ways. The authors describe how neurosurgical robots have become more "active," progressing from simple guides for stereotactic procedures to motion-scaled, tremor-filtered, master-slave systems. The statement that the newer active robots are more autonomous may not be correct (1). Autonomy implies that the robot performs a task automatically, i.e., without the control of the surgeon. Although some systems such as the CyberKnife (Accuray, Inc., Sunnyvale, CA) perform tasks automatically, dexterous master-slave surgical robots are under real-time position control by the surgeon. The robotic link simply upgrades the surgeon's hands, permitting finer motion with a magnified sense of touch.

The authors classify robotic systems in three categories on the basis of how the surgeon interacts with them: supervisory, telesurgical, and shared systems. An example of the shared configuration is the SteadyHand system developed at Johns Hopkins. It does not permit motion scaling, because the surgeon directly manipulates tools attached to the robot arm. The statement that these shared systems are designed to increase the precision of surgery "to the level enabled by microscopy" is bold if relying on tremor filtering alone, as motion scaling also must be considered.

The situation is different in teleoperator systems, in which the surgeon controls the slave robot through a master device such as a haptic hand controller. Because the link between master and slave is electronic, it is possible to scale coarse motion by the surgeon to fine motion by the robot. However, motion and forces cannot be scaled indefinitely because the system eventually becomes unstable. Related to stability is the concept of latency. The transparency of the haptic interface is limited by the amount of time it takes to position information from the master to reach the slave and for force information to be communicated back to the master. Even with improved low-latency communication channels between master and slave, only a handful of long-distance data exchanges per second are possible, because the signals can travel no faster than the speed of light. Therefore, telesurgery to remote locations of the world with high-fidelity haptic feedback may not be possible.

Nathoo et al. discuss the need for the robotic system to adapt to the deformability and shifting of the brain during surgery. This is important: despite knowing the absolute position of the robot end-effector, the location of a lesion may move relative to the preoperative scan, in which case the relative position between end-effector and lesion is lost. NeuroArm, a robotic system developed at the University of Calgary, will deal with brain-shift by providing near-real-time magnetic resonance images at the robot workstation on a flat panel display (2, 3). Alternatively, robotic systems may be used much like they are in contemporary surgery through immersion in an electronic visual and haptic environment.

Robotic platforms enable new types of intelligent tools no longer constrained by the human hand. These may come to fruition long before robots are capable of intelligent, autonomous thought. The reality of surgical robots as the standard of care for neurological disorders is speculative and will require considerable interaction between multiple disciplines including medicine, engineering, computer science, and physics. There are, however, increasing numbers of people and emerging societies committed to this endeavor. The evolving robotic systems, especially those with haptics, provide the opportunity for virtual surgery. This will be particularly important as mechatrons enter our operating rooms.

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