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Robotic Neurosurgery

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1. Introduction

The field of neurosurgery has made a concerted effort in adapting and incorporating advancing technologies into the operative field, adapting new techniques and devices successfully in an effort to increase the safety and efficacy of brain and spine surgery. Diligent efforts are made to minimize normal tissue trauma during surgical intervention while maximizing clinical outcomes. Among these adaptations are the emphasis on surgical robotics. That surgical robots have not found widespread clinical utilization in neurosurgical procedures is debatable, because the term "robot" itself has several definitions. For our purpose, we will focus our discussion to mechanical devices used in the operating field of neurosurgery that ultimately give the operator, i.e. surgeon, ability to control the device through automation or remote control.

Name	Type	Function	Advantages	Disadvantage
Automated Positioning System	Supervisory controlled	Radiosurgery	Precision	Limited function
NeuroMate	Supervisory controlled	Biopsy, MDS	Precision	Limited function, cost
Minerva	Supervisory controlled	Biopsy	Precision	Limited function, safety issues
Evolution 1	Shared control	Pedicle screws, ETV, transphenoidal	Dexterity enhancement	Lack of sensory feedback, cost
da Vinci	Telesurgical	Urologic, gynecologic, and general surgery	Dexterity enhancement	Lack of sensory feedback, not equipped for bone/disc work
NeuroBot	Telesurgical	Tumor resection	Dexterity enhancement	Lack of sensory feedback, cost
Cyberknife, RoboCouch	Supervisory controlled	Radiosurgery	Precision	Limited function
SpineAssist	Supervisory controlled	Pedicle screws	Precision	Limited function, cost

Table 1. Robotic surgical devices with FDA-approved and experimental neurosurgical applications

Source: Medical Robotics, Book edited by Vanja Bozovic, ISBN 978-3-902613-18-9, pp.526, I-Tech Education and Publishing, Vienna, Austria

Technological advances in the field of robotics had clearly been incorporating into the operating room through the use of microscopy, navigation, instrumentation, optics, and imaging (Nathoo et al., 2005). However, the use of a mechanical device, whether through automation or remote control, to ultimately manipulate the instruments directly in contact with a patient is relatively new to brain and spine surgery. Since Kwoh et al. attempted a robotic brain biopsy in the late 1980s, growing interest in this field and its potential clinical benefits has encouraged the development of multiple systems (Kwoh et al., 1988). As with all novel instrumentation, the role of these systems must be clearly defined.

Among neurosurgeons this is particularly challenging, because the concepts of manual microsurgical techniques are already embedded effectively and successfully in standard practice. Approaching central nervous system pathology within millimeters through small working channels surrounded by vital tissue almost defines the subspecialty. Manual dexterity and minimization of coarse movement are an essential part of neurosurgery. Integration of surgical robotics is, therefore, an interesting dilemma and great promise. Although its theoretical advantages seem most suited to neurosurgical disease, the state of the art and technology has not yet matched the theory and expectations. Despite these practical hindrances, advances coupling clinical, and scientific discovery, continue to expand the notion of what is possible. This paper reviews some of the more promising systems in neurosurgical robotics, including brain and spine applications, in use and in development (Table 1).

2. Brain Surgery

There has been multiple robotic approaches to address the specific challenges associated with interventions on the brain (Benabid et al., 1987; Benabid et al., 1992; Drake et al., 1991; Karas and Chiocca, 2007; Kwoh et al., 1998; Nathoo et al., 2005). Deep intracranial pathology requiring manipulation of or direct trauma to the parenchyma has inspired devices that may minimize damage to normal tissue (Drake et al., 1991; Kwoh et al., 1988). While this is not meant to serve as a review of surgical robotics in general, an understanding of the subtypes of system available may be helpful. Nathoo et al. eloquently propose a classification based on the robot–surgeon interaction (Nathoo et al., 2005). Three systems are described. The first is a supervisory-controlled robotic system in which the robotic intervention is preplanned and programmed and then supervised by the surgeon as it carries out its programmed movements autonomously. The second is a robotic telesurgical system in which the robot is manipulated by the surgeon in real time through remote control, with limited feedback to the operator. The third is a shared control system in which the surgeon directly controls the movements of the robot as the robot enhances the surgeon's skills through dexterity enhancement, a term that generally describes mechanical solutions to human limitations, including physiologic tremor reduction.

As previously stated, development efforts have been focused on gaining access to deep pathology or structures (such as the third ventricle) with limited trauma to the normal brain. Coupling these devices, therefore, with image-based navigation systems and developing controlled, precise target-acquisition capabilities have been crucial advances in attempting intracranial procedures. In general, with these resources, existing models focus their technology on specific tasks.

The most widely used and simplest example of robotic assisted neurosurgery for the brain pathology is the latest model of the Leksell Gamma Knife Radiosurgical system. This is a supervisory-controlled robot that uses an Automated Positioning System (APS) (Elekta, Stockholm, Sweden) to adjust the patient's head within a collimator automatically, based on a

predetermined stereotactic radiosurgical plan. Thus this latest model of Leksell Gamma Knife eliminates multiple manual steps that were required by the Neurosurgeon and the Radiation Oncologist of confirmation and reconfirmation of the head position prior to delivery of the therapy. Most patients requiring Gamma Knife therapy need multiple doses of different intensity and position for proper therapeutic effect, thus confounding the manual manipulation dilemma. Several studies have confirmed the benefits of such automation, confirming shorter treatment times, reduced exposure of patients and personnel to radiation, and greater ability to deliver radiation to an increased number of smaller isocenters, thereby reducing the maximum dose to the target (Regis et al., 2002; Tlachacova et al, 2005).

For the purpose of lesion biopsy within the brain, navigation with image-guidance systems is common practice. To take this a step further, attempts to automate the brain biopsy procedure with robotic arms have been performed. The NeuroMate (Integrated Surgical Systems, Sacramento, CA, USA) robotic surgical system was the first FDA-approved robotic device for neurosurgery (Benabid et al., 1987). This system involved a passive robotic arm which moves in a pre-programmed direction to a specific site defined by integrated neuronavigation systems for stereotactic biopsy or functional neurosurgical applications. The Minerva (University of Lausanne, Lausanne, Switzerland) which followed, attempted to account for brain shift by placing the robotic arm within a CT scanner to provide real-time image guidance (Glauser et al., 1995). Safety issues forced the discontinuation of this device (Nathoo et al., 2005). Indications for the NeuroMate continue to expand as image-guidance technology advances. Recent studies have proven its localization and targeting capabilities are comparable with those of standard localizing systems (Li et al., 2002). Varma et al. achieved good accuracy with a frameless application of this system in microelectrode placement for treatment of Parkinson's disease (Verma et al., 2003).

Another system, the Evolution 1 robotic system (Universal Robot Systems, Schwerin, Germany) has been tested for several neurosurgical applications. Its been used successfully for endoscope-assisted transphenoidal pituitary adenoma resections. However it has been deemed too cumbersome and time-consuming to justify their use (Nimsky et al., 2004). More recently this system has been used for endoscopic third ventriculostomy (ETV) in six patients with hydrocephalus secondary to aqueductal stenosis (Zimmerman et al., 2004). Specifically, the robotic arm was used to precisely and reliably guide an endoscope to visualize the floor of the third ventricle. The ventriculostomy was performed manually by the surgeon through working channels in the endoscope, which was held rigidly by the robot. Theoretical advantages of this system over surgeon-alone ETV are precision targeting through image-guidance coupling and dexterity enhancement, which eliminates micro movements of a hand-held scope. Thus far there is no evidence supporting a clinical or outcome benefit of robotic over manual ETV, despite the measured differences.

Asides from the interventions requiring a single instrument or endoscope-stabilization solutions, telesurgical systems with multiple arms for both variable instrumentation and endoscopy are currently available in other surgical specialties (Nathoo et al., 2005; Stoianovici, 2000). The Neurobot telerobotic surgical system has been used successfully in complex procedures requiring simultaneous retraction and dissection (Hongo et al., 2002). Goto et al. describe a robot-assisted craniotomy in which the NeuRobot is used to resect superficial portions of an intraaxial tumor on a live human subject, citing dexterity enhancement as one of the potential advantages (Goto et al., 2003). At our institution several da Vinci surgical systems are available for both clinical use and research purposes. It has become standard instrumentation for prostatectomy and other urological procedures, and is

FDA-approved for general and gynecologic surgery also. Given its tremor reduction, motion scaling capabilities, multiple working arms, and patented Endowrist (Intuitive Surgical, Sunnyvale, CA, USA) technology which enables for full range of motion at the instrument head comparable with that of the human wrist, this device was tested at our institution for several neurosurgical procedures also. In our experience with cadaveric trials of end-to-end ulnar nerve reanastomosis, lumbar discectomy, intradural spinal dissection, and complex intraventricular surgery, significant obstacles to brain and spine applications still remain (Oral Presentation, AANS/CNS Section on Pediatrics, Denver, USA, 2006).

These obstacles, however, do provide insight into some of the necessities of robotic neurosurgery, which require both software and hardware changes. Specifically, the traditional endoscope with working channels allows for one tract through normal tissue to the ventricles rather than multiple tracts to accommodate instrumentation. This traditional model coupled with Endowrist technology may provide the added benefit of a greater range of motion within the ventricular system, which is otherwise impossible to achieve manually. Robotic devices focused on accurate localization may also move, or be manipulated, in such a way as to precisely acquire a target at a deep location at the expense of normal tissue at a more superficial level. For example, an endoscope positioned robotically to view the floor of the third ventricle may pivot dangerously at the cortex or foramen of Monroe and fornix. Docking after target acquisition, therefore, with continued mobility only distally is ideal. Finally, a clear disadvantage within all categories of surgical-robotic models is the lack of feedback to the operator. Although visual feedback has improved significantly with advances in optics and image-guidance, other sensory feedback is lagging. Position, velocity, or acceleration of the instruments may be recognized through a combination of visual cues and, for telesurgical or shared-surgical models, proprioceptive cues. Without complete sensory feedback, however, other significant sensations are lost, including force on adjacent structures or characteristics of manipulated tissues, for example compliance, texture, pulsatility, or elastiscity. Active research in this aspect of robotics continues and will be crucial in the integration of these systems into neurosurgery given the arguably absolute necessity of such feedback when operating within the central nervous system (Gray & Fearing, 1996).

3. Spine Surgery

There is a growing interest in the field of spine surgery to incorporate a robotic arm to image-guidance in order to assist with surgical interventions on bony landmarks. Several robotic systems have been developed to address the challenges encountered in spinal surgery. As with brain applications, these devices are enhanced significantly by advances in intraoperative image-guidance. In general, research in this area has focused on accurate placement of spinal instrumentation, citing the theoretically increased accuracy that robotics offers (Garcia-Ruiz et al., 1998; Goto et al., 2003; Taylor et al., 1999). In radiosurgery, robotic solutions to spine motion with respiration have also been extremely useful (Adler et al., 1999).

As with intracranial radiosurgical applications, the most common robotic subtype in spinal stereotactic radiosurgery is a supervisory-controlled system. Cyberknife (Accuracy, Sunnyvale, CA, USA) relies on a predetermined plan which targets spinal pathology for focused beam radiotherapy. By use of feedback mechanisms this system can adjust its trajectory to correct for patient movement, most of which result from respiration. This novel use of robotics has been expanded to intracranial use also, given the possibility of brain shift. A recent addition to the Cyberknife system is the RoboCouch Patient Positioning System (Accuracy), which uses similar technology to reposition the patient during the course of treatment.

Other supervisory-controlled systems have been developed for conventional spinal surgery as well (Chop et al., 2000; Lieberman et al., 2006). Specifically, devices coupled with image-guided navigation systems have been tested for accurate pedicle screw placement. Most recently, Lieberman et al. tested the SpineAssist (MAZOR Surgical Technologies, Caesarea, Israel) miniature robot for both pedicle and translaminar facet screw placement (Lieberman et al., 2006). Again, this device consists of a passive arm, which mounted on a fixed part of the axial skeleton. Motion of the robotic arm is defined by preoperatively planned screw trajectories, and is supervised by the surgeon. This and other robots with similar functionality have been tested successfully on human subjects, and the SpineAssist device is currently FDA-approved for spinal instrumentation.

As stated previously, we have tested several procedures with the da Vinci Surgical System at our institution, including lumbar discectomy, and intradural dissection. Because of the focused function of most robotic devices, it is clear that operations requiring both bony and soft tissue manipulation at different stages would also require human intervention at some point or multiple limited-function robots. Even the multifaceted design of the da Vinci telesurgical robot with multiple arms is limited in spinal surgery. The range of forces provided by this device, while adequate for abdominal or gynecologic surgery, does not enable use of a drill for bone remodeling, nor does it facilitate extraction of disc material. Without this capability, discectomy is nearly impossible, and intradural intervention requires conventional manual laminectomy. In a cadaveric study, after laminectomy, the da Vinci robot was used to open and close the dura and to separate nerve roots in the cauda equina from the filum (Karas & Chiocca, 2007). These maneuvers were performed with relatively little trauma despite only visual feedback.

4. Conclusion

Surgical robots have clearly affected the current practice of neurosurgery through several FDA-approved devices, most notably in the realm of radiosurgery. It is clear, however, that while the field of surgical robotics advances, attention must be given to the details of brain and spine surgery and surgical anatomy. Integrations of new focused technologies then can be adapted more easily into the neurosurgeon's already highly specialized operating environment. Creating the future of dexterity enhancement, automation, and sensory feedback, is of most value to surgical robotics if it can be studied in the context of each specialty. The robots most widely used in neurosurgery have been products of this contextual research, which concentrated on central nervous system-specific solutions. Attempts to adapt other instrumentation for neurosurgical use have proven to be less effective.

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophageal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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