

Roles of Stereotactic Surgical Robot Systems in Neurosurgery

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An important trend of surgical procedure is minimally invasive surgery (MIS). Neurosurgery is an important part of the surgical field that may lead in trends. The MIS provides surgeons use of a variety of techniques to operate with less injury to the body than with open surgery. In general, it is safer than open surgery and allows patients to recover faster and heal with less pain and scarring.

There are various techniques and medical devices for improving the MIS. Recently, robotic surgery was introduced to MIS. Advanced robotic systems give doctors greater control and vision during surgery, allowing them to perform safe, less invasive, and precise surgical procedures.

On the one hand, several robotic systems have been developed for use in neurosurgery. Some of those neurosurgical robots have been commercialized and used in clinical practice while others have not been used because of safety and ethical issues. This paper provides a brief review on robotic systems for neurosurgery, primarily focusing on commercially available systems.

Key words: Stereotactic Surgery; Surgical Robot System; Radiosurgery

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INTRODUCTION

There are several special fields in neurosurgery, such as vascular, brain tumor, pediatric, spine and stereotactic functional surgery. Among them, stereotactic functional surgery is the representative field of neurosurgery that uses minimally invasive surgical intervention. It uses a three dimensional coordinate system to accurately localize targets shown in the patient's diagnostic images and to perform medical treatments on them. The term "stereotaxy" comes from the two Greek words, stereos meaning "3D" and taxis meaning "orderly arrangement". The concept for human neurosurgery was first introduced in a paper in 1908 by Victor Horsley and Robert Clarke [1]. Several stereotactic devices such as the Leksell frame [2], Brown-Roberts-Wells (BRW) frame [3], and Zamorano-Dujovny (ZD) frame [4] have been developed and used for stereotactic neurosurgeries. Advances in medical

imaging technologies led the stereotactic surgery to even more applications. It is now widely used for tumor resections, biopsy, shunt, surgical targeting of electrodes, epilepsy, stimulation, and radiosurgery. Although, theoretically, stereotactic surgery can be performed on any part of body, its application has been confined to brain surgery because it is very hard to set up a coordinate system on a soft body reliably.

Ever since an industrial robot was first medically used in 1985, the medical robotics field has been rapidly growing based on a combination of technological improvements of robotics and advances in medical imaging and computer graphics technologies. Various types of robotic devices have been used in laparoscopy, neurosurgery, orthopedic surgery, and other medical disciplines. For neurosurgery, several systems were developed over the last three decades; some of those neuro-robot systems have been commercialized and used in clinical practice while others have not because of safety and ethical

reasons. This review aims to provide an overview of several robotic neurosurgery systems which are stereotactic based and commercially available.

ROBOTIC SYSTEMS FOR STEREOTACTIC SURGERIES

1. PUMA 200

Brain surgery usually involves accessing a target in the deep brain area, the ability of a surgical robotic system that moves accurately based on medical images might be beneficial for neuro surgeries [5].

A robotic surgery system was first used in human surgery in 1985. An industrial robot, Programmable Universal Machine for Assembly (PUMA) model 200, and a stereotactic frame were used for intracranial biopsy based on a computed tomography (CT) image [6]. PUMA 200 was a human arm type robot with six degrees of freedom, and it moved on the trajectory for a biopsy while maintaining the probe's orientation determined on a preoperative CT image. The Brown-Roberts-Wells (BRW) stereotactic frame was used for localization of targets and registration. The registration between the CT image and the robot was performed using fiducials on the stereotactic frame attached to the patient's skull.

2. Neuromate

Neuromate (Renishaw Mayfield SA, UK) was the first neurobotic system approved by FDA and commercially available [7]. Neuromate is an image-guided and computer-controlled robotic system with five degrees of freedom. It was specifically designed for stereotactic surgical applications to reduce human errors and operative time. The system can be incorporated with medical images such as computed tomography (CT), magnetic resonance imaging (MRI) and angiographic images, and with a stereotactic frame to locate a probe for biopsy or to implant electrodes to deep brain structures [8]. Its surgical applications include biopsy, deep brain stimulation (DBS), stereoelectroencephalography (SEEG), stereotactic applications in neuroendoscopy. The Neuromate robot can be used with a stereotactic frame, or in frameless mode to reduce patient trauma. Regarding the application accuracy of Neuromate, it was reported that a frame-based configuration with sub-millimeter accuracy was more accurate than a frameless configuration having 1.95mm accuracy [9].

With the planning software VoXim™ (IVS Technology GmbH, Germany), it is possible to perform precise image-based

planning and visualize multiple trajectories. The robotic system includes safety features in terms of software and hardware. Thus, a surgeon might define a safety zone around the patient's head where the robot arm needs to reduce its speed for safety in the planning software [10].

3. ROSA

ROSA robotic surgery system was developed by a French company, Medtech, to assist typical needle-based neurosurgeries like brain tumor biopsies, tumor resections, epilepsy surgery, deep brain stimulation, cerebral cortex stimulations, and endoscopic procedures [11]. The ROSA system can be applied to intracranial procedures requiring surgical planning based on preoperative image data, patient-robot registration, and precise manipulation of instruments.

With six degrees of freedom in the robotic arm, the ROSA system provides increased access to the surgical area and freedom in selecting trajectories for surgical instruments with high dexterity. Advanced haptic capability of the ROSA system provides surgeons easy guidance of instruments by hands inside boundaries set up during the planning stage. Along with the haptic manipulation mode, the surgeon can easily perceive the surgical field due to the real time navigation of the surgical instruments overlaid on the preoperative medical images.

The ROSA system provides a unique method for patient registration, which combines precise robotic movement with non-invasive laser measurement. This method simplifies the registration procedures by removing a stereotactic frame and fixed fiducial markers. According to the Medtech's webpage, the ROSA system is being used for neurosurgical procedures in clinical use in about 70 hospitals in Europe, the United States, Canada, and Asia [12].

4. Renaissance

Mazor Robotics developed the Renaissance system, which was previously named SpineAssist [13]. In early 2004, Mazor Robotics first received the Conformite Europeenne (CE) mark with SpineAssist, which was the first commercially available guidance system for spine surgery. As the current flagship product, the Renaissance Guidance System was released for spine and stereotactic brain surgery in 2011 after receiving FDA clearance and CE mark [14].

The device consists of mounting platforms which are rigidly attached to the patient's spine and a soda can-sized robot that is directly placed on the mounting system. A surgeon

creates surgical plans in a virtual 3D environment, and the robotic system provides tool guidance based on the surgical plans. Rigid attachment to the patient ensures maximum surgical accuracy throughout the procedures. The Renaissance Guidance System can be applied to a wide variety of procedures including minimally-invasive surgeries, pedicle screw fixation, vertebral augmentation, biopsies, and electrode implantation procedures.

Renaissance provides special add-ons which are fixed on the mounting platforms and conventional C-arms, respectively. Two fluoroscopic images are taken and matched to a patient's pre-operative CT using 2D/3D image registration methods. An assessment study reported that implantation accuracy was increased using SpineAssist and evidence that more percutaneous implantations might be performed with SpineAssist [15].

5. CyberKnife

Radiosurgery is a radiooncologic treatment which focuses ionized radiation to the patient, primarily to treat tumors [16]. By directing beams to the tumor from various orientations, high-dose radiation is transferred to the tumor while the surrounding tissue receives significantly less radiation.

CyberKnife (Accuray Inc.) is a frameless radiosurgery system developed for treating benign and malignant tumors [17]. The system consists of a robotic arm which mounts a radiation source and a robotic patient positioning system called RoboCouch. A compact X-band linear particle accelerator (linac) produces X-ray radiation which is collimated to produce circular radiation fields. The RoboCouch system is a patient positioning system with six degrees of freedom providing sub-millimeter accuracy for whole-body radiosurgery. Combined with the robotic mobility of CyberKnife system, RoboCouch provides full accessibility to tumors anywhere in the body [18].

Intraoperative X-ray images are used to perform a 2D/3D registration using digitally reconstructed radiography (DRR) on a patient, a preoperative CT image, and the robotic system. Then, the robotic arm deliver the pre-planned radiation with a wide range of orientations. With this imaging technology, the CyberKnife system can deliver radiation with an accuracy of 0.5mm without using mechanical head frames attached to the patient's skull [19]. A synchrony system can be optionally used to track moving targets during treatment. The system uses surgically inserted fiducials and LED markers mounted on the patient's skin to correlate the motion between external

and internal markers [20]. Also, a motion prediction algorithm is used to compensate the latency between robot motion and image acquisition.

6. TrueBeam STx

Novalis with TrueBeam STx (BrainLab Inc. and Varian Medical Systems) is also a frameless system with a linac as a radiation source [21], but beam shapes are adjusted using micro multileaf collimators (mMLCs) to match the borders of the target tumor [22]. This shaped beam radiosurgery provides better exclusion of normal tissue and better dose homogeneity only to the intended target. Similar to CyberKnife, intraoperative X-ray images are registered to a pre-operative CT, and skin-mounted fiducials are optically tracked in real-time to compensate respiration-related movement. For patient positioning, a robotic couch with six degrees of freedom is provided. A distinction between Cyberknife and Novalis is that Cyberknife can move the radiation source with more degrees of freedom around the patient while Novalis can provide a volumetric intensity modulated radiotherapy (IMRT) in a single rotation of the treatment machine, called RapidArc, around the patient [23].

CONCLUSIONS

Since developed by Horsley and Clarke in 1908, stereotactic neurosurgery has become an active research field because it allowed for targeting and treatment of intracranial lesions that were not possible to treat in the past. With revolutionary advances in medical imaging, robotics, and information technologies, image-guided computer assisted interactive surgical procedures are quite common in current operating rooms. Medical robots have great potential to improve precision and capabilities of surgeons when performing surgical procedures. It will not take too long before medical imaging devices such as CT, MRI scanner are integrated with a robotic system in each neurosurgical operating room to meet the requirement of image-guided minimally invasive surgery.

Several companies are selling robotic systems for neurosurgeries, but the total number of installed system is very small. And the market does not grow rapidly unlike the area of industrial robotics, which grew rapidly in 1970s and 1980s. The application of robotics in medicine is not mature, and many questions regarding their effectiveness and safety still remain open. Nevertheless, it is believed that the benefits of

neurosurgical robotic system will be getting apparent, and this will lead to a continuous growth in their use.

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