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Review of Robotic Technology for Keyhole Transcranial Stereotactic Neurosurgery

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***Abstract*—Stereotactic apparatus to guide surgical devices started being researched in 1908, yet today's neurosurgery still rely on stereotactic frames developed almost half a century ago. Robots excel at handling spatial information and thus are an obvious candidate for guiding instrumentation along precisely planned trajectories. In this review, we introduce the concept of stereotaxy and we then describe standard Deep Brain Stimulation (DBS) surgery. Neurosurgeons' expectations and demands about the role of robots as assistive tools are also addressed. We listed and critically reviewed the most successful robotic systems developed specifically or enabled for keyhole transcranial stereotactic neurosurgery. A comprehensive summary details the strengths and drawbacks of each robotic system, emphasising the differences between them. Finally, a critical analysis is made about the listed robotic systems' common and distinct features, and whether they are considered advantages or not. Some essential yet not so obvious characteristics of these systems are also described, along with future perspectives. In the end, all robotic systems follow a very similar and structured workflow despite the technical differences that set them apart. No system unequivocally stands out as an absolute best. Technological progress trend is pointing towards the development of miniaturised, cost-effective solutions with more intuitive interfaces.**

***Index Terms*—Image-guided surgery, Keyhole transcranial neurosurgery, Stereotaxy, Robotic technology.**

I. Introduction

STEREOTAXIS from the Greek meaning "three-dimensional, orderly arrangement" is based on a principle that a volume like the brain, can be mapped according to a specific coordinate system using precise measurements (Gabriel and Nashold, 1998). The stereotactic technique relates to a Cartesian coordinate system and employs mathematical concepts to identify points in space that result from the intersection of 3 orthogonal planes: anteroposterior, lateral and vertical (Gildenberg, 1998; Roberts, 1998). The fusion of mathematical, anatomical and neurological fundamentals enable neurosurgeons to identify and access stereotactic targets without direct visualisation (Rhodes et al., 1982).

The ability to correlate anatomical data to an objective spatial mapping opened doors to minimally invasive and safer structural stereotactic, also known as "keyhole neurosurgery" procedures like: biopsies, endoscopy, hematoma/abscess evacuation or radio-surgery; Stereo-Electroencephalography (SEEG) and also for functional stereotactic procedures based on destructive or augmentative methods – e.g. Deep Brain Stimulation (DBS) (Benabid, 2003).

Stereotactic neurosurgery is closely related to the stereotactic frame (Horsley and Clarke, 1908). Since the first apparatus for human stereotaxy reported in 1947 by Spiegel et al. (1947), stereotaxy quickly became a subject of interest, and around 1950's over 40 different stereotactic frames were designed and reported (Gildenberg, 1998). Gabriel and Nashold (1998) listed several approaches in 5 categories: i) translational systems, ii) burr-hole mounted systems, iii) arc-centred, iv) interlocking arcs, and most recently v) frameless (Galloway, 1998a).

Despite the conceptual differences between stereotactic frames, all share the common goal of establishing a rigid relationship between the patient's head/brain and the outer space where screws, drills, probes and other devices are handled (Benabid et al., 1998). However, frames are often held as cumbersome and inflexible devices, often uncomfortable to the patient and with limitations in reaching insertion trajectories (Gabriel and Nashold, 1998).

Only a handful of robotic systems for assistive robotic neurosurgery were released into the market, although this idea has been a research target since 1985 (Kwoh et al., 1988). Computer-driven technology such as robotic systems, unlike purely mechanical stereotactic frames, enable more intuitive interfaces. Robotic systems excel at handling spatial information and directives, which enables the neurosurgeon to focus entirely on the surgical procedure. The precision, steadiness and tirelessness of robotic systems are compelling arguments in favour of its use (Beasley, 2012). Additionally, robotic systems enable precise guidance of neurosurgical instrumentation, motion filtering and imposing physical restrictions to avoid "no-go" zones. On the other hand, there is still room for improvements, particularly in terms of reducing costs, developing smaller and more powerful robotic systems (Marcus et al., 2014; Mattei et al., 2014).

The paper is organised as follows. Section II describes a standard Deep Brain Stimulation (DBS) surgery in order to illustrate the steps involved in a typical stereotactic neurosurgery. Section III addresses the expectations and demands that neurosurgeons have concerning the potential role of robots as assistive devices. Section IV lists robotic systems and projects that either reached the market or achieved clinical clearance for assistant stereotaxy (endovascular and

radiosurgery enabled robotic platforms not included). Finally, current perspective and conclusions are presented in sections V and VI, respectively.

II. Stereotactic Neurosurgery

To explain when and how a robotic manipulator can be of use, why it would improve both working conditions and the final outcome, we present the traditional workflow of a stereotactic neurosurgery, more specifically for DBS with micro-electrode recording (MER). The bilateral DBS surgery here described was conducted in a patient with Parkinson's disease. More information about DBS surgical technique can be found in (Perlmutter and Mink, 2006; Seijo et al., 2009; Starr et al., 2010; Stewart, 2010).

Following the paradigm of Image-Guided Surgery (IGS), the patient initially undergoes a Magnetic Resonance Imaging (MRI) and/or any anatomo-functional imaging scan. On the day of surgery, and after attaching the stereotactic ring (Fig. 1a) to the patient's head, a Computed Tomography (CT) scan is taken. The MRI and CT scans are *registered* to the stereotactic space, i.e. – the transformational relationship between the two three-dimensional spaces is determined (Galloway, 1998b). Four fiducial localisation plates attached to the stereotactic ring during the CT scan (Fig. 1a), allow the calculation of the transformation between the image space with reference on the anterior-posterior commissure line, and the stereotactic reference frame.

In the planning software, the medical team selects the target and entry points of the electrode insertion trajectory, avoiding vessels and ventricles. Based on the selected trajectories, the planning software computes the stereotactic frame coordinates for each electrode.

Inside the operating room a phantom device is used to visually confirm the stereotactic frame coordinates (Fig. 1b). The phantom is attached to a stereotactic ring (similar to the one fixated on the patient's skull) and simulates the target point to be reached by the electrode. The stereotactic frame is mounted in the phantom's stereotactic ring and adjusted to the desired coordinates. A stylet is placed in the stereotactic frame guide and the computed coordinates are confirmed if the stylet tip and the phantom tip are coincident.

The frame is removed from the phantom, placed in the patient's stereotactic ring and the stylet is used to mark the scalp entry point. Then the frame is moved aside to make the scalp incision and drill the hole in the skull to access the brain (Fig. 1c-1d). The frame is adjusted again to advance the electrodes/cannulas to the defined depth (1e).

Multi micro-electrodes are used to map the sensorimotor region by recording the neuroelectrical activity near the planned target. Initially, these electrodes are positioned along the planned trajectory with the help of guiding cannulas, 10mm to 15mm before the target. After, they are iteratively lowered – millimetre by millimetre – until 5mm from the target and then half a millimetre between iterations, recording the neuroelectrical signals at each step. In the end, data recorded are analysed to select the most proximal location to the sensorimotor region within the nucleus (Fig. 1e).

The same recording micro-electrodes have a macro-stimulation lead, which is used to stimulate the previously located sensorimotor region. Following again an iterative approach, the current and the depth of leads is increased (Fig. 1e-1f). At each step, the team of neurologists qualitatively evaluates the patient's symptoms seeking the best response and side effects.

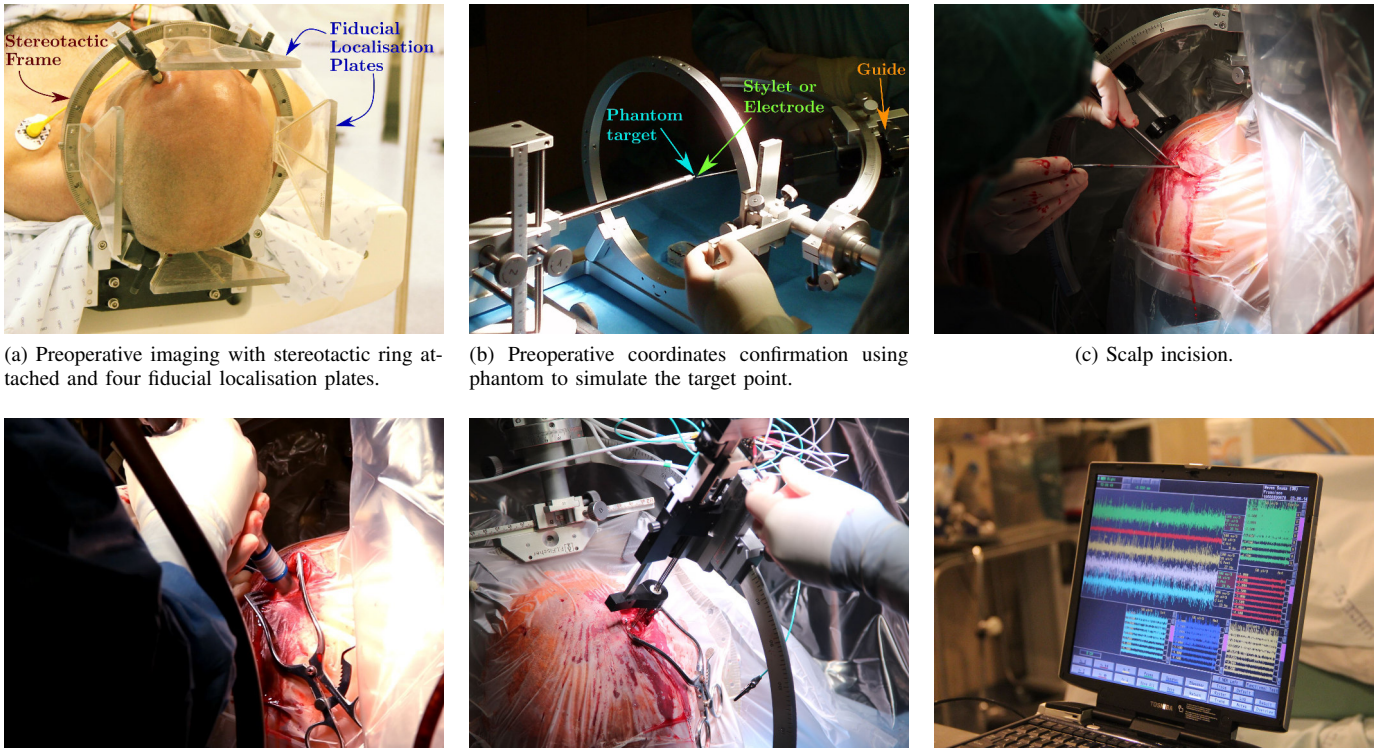
After finding the ideal electrode placement and stimulation signal properties, the micro-electrodes are replaced by a definitive quadripolar macro-electrode. Intraoperative imaging is used to check if the macro-electrode placement coincides with the micro-electrode position. The macro-electrode is later connected to an Implanted Pulse Generator (IPG) or neuropacemaker. If a bilateral brain stimulation is required, all intraoperative processes must be repeated for the other side. Due to the long duration of the procedure, the neurosurgeon can chose to implant the IPG at the same day or in a delayed/staged fashion.

III. Robotic assistant: neurosurgeons' expectations and demands

How do robotic systems improve the work conditions for neurosurgeons, for neurologists and to other staff? What tasks can be delegated to the robot? What are the benefits for the patient? What can be expected of a neurosurgical robot? These are some of the most common and fundamental questions often posed to and by developers regarding robotic neurosurgery that will be addressed below.

As stated previously, a typical stereotactic surgery lasts several hours through which the surgical team must remain completely focused. Upon attending to stereotactic surgeries and *brainstorming* with neurosurgeons and robotic engineers, we were able to answer the first two questions (somewhat related) and conclude that a simple and intuitive robotic system may improve the standard procedure in various aspects:

- Enable coordinates and electrode's path information to be managed between the planning software and the robotic controller software, instead of manually handling this information.
- Avoid stereotactic frame and driver mechanical slacks or loose parts.
- Avoid the slow process of mounting and setting frame and driver coordinates for both phantom and patient, each time.
- Allow neurosurgeons to select and insert electrodes in eccentric trajectories, overcoming the constraints imposed by stereotactic frame apparatus, which is extremely helpful when more than a single trajectory is needed, such as during SEEG, where up to 20 electrodes need to be inserted in a single procedure.
- Enable the robotic manipulator to handle multiple end-effectors and surgical instrumentation to execute restrained skull drilling and swift positioning of electrodes with improved precision. The manipulator can constraint these tasks to be carried specifically along the predefined path, instead of executing them based on a marked entry point.



(a) Preoperative imaging with stereotactic ring attached and four fiducial localisation plates.

(b) Preoperative coordinates confirmation using phantom to simulate the target point.

(c) Scalp incision.

(d) Skull drilling.

(e) Placement of multi micro-electrodes to register neurological signals and stimulate target structures.

(f) Micro-electrode recording and calibration of macro-stimulation parameters.

Fig. 1. Deep Brain Stimulation surgical procedure steps.

- Enable medical teams to easily take control over the task of advancing the depth of electrodes while evaluating the patient's symptoms by simply interacting with a robot graphic interface, which aids neurosurgeons on that task.
- Flexibility and ease in changing the entry point once the burr hole is performed and an unexpected vascular structure is encountered after opening the dura matter.
- Reduce the risk of data loss or human errors.
- Enable an online monitoring of the instrumentation tips absolute coordinates based on their physical dimensions and on the manipulator position relative to the base referential.
- Opens the possibility for frameless surgery under robotic guidance.

It is important to note that, even though frameless surgery implies no frame, the transformation between the instrument guiding device and the patient must be constant. The most common approach to this problem relies on the use of a Mayfield 3-point pin fixation device (Integra LS, Plainsboro, New Jersey), to immobilise the patient's skull. Then, a rigid link connecting the Mayfield and the instrument guiding device, ensures the constant transformation.

Robotic systems enhance accuracy, precision and steadiness (Cardinale and Mai, 2011) which directly reflects into less intraoperative complications and have a positive impact on the patient's outcome (Camarillo et al., 2004; Nathoo et al., 2003). Not only the patient but also the healthcare institution benefits from shorter patient recovery times and less occupancy rates.

When consulted about the robotic system expectations for stereotactic neurosurgery, neurosurgeons look forward to: i) a simple system of intuitive usage, ii) a cost-effective solution, iii) a small and easily mountable and movable device. Thus, aside from the main goal of positioning and manipulating surgical equipment, human factors and integrability of the robotic system are the most sought assets and thus, should be targeted by engineers when devising a robotic platform for stereotaxy.

IV. State of the Art Robotic Systems

Since the first report of a robotic neurosurgical system in 1985, a wide range of neurosurgical solutions have been brought to stage (Kwoh et al., 1988). To keep the paper brief, we chose to include the most successful robotic systems or projects towards keyhole transcranial stereotactic neurosurgery that either reached the market or were clinically tested, with reported *in vivo* results[1] (see TABLE I). Robotic platforms for endovascular or radiosurgery were not included in this review. The listed robotic systems were divided in three categories according to the user-interaction (see Nathoo et al. (2005)):

- *Supervisory Controlled*, the robot motion performed during the operation is explicitly or implicitly specified by the surgeon offline. During the procedure the robot autonomously moves under surgeon supervision.

[1]The Robocast and NeuRobot projects did not report clinical trials, but were involved in major european funded programs, and were included for their contribution.

- *Telesurgical*, the robotic manipulator (slave) is directly controlled by the surgeon through an input device like a joystick (master) usually endowed with force feedback.
- *Shared Control*, surgeon and robot share the control over the surgical instrumentation. The surgeon still controls the procedure while the robot provides steady-hand manipulation or active-restrain over surgical safety areas.

A. Specific for Stereotactic Neurosurgery

1) SurgiScope: SurgiScope (ISIS Robotics, Saint Martin d'Hères, France) development started in 1989 from a cooperation between University of Grenoble and the industrial company AID, and is currently available at an operating level (Benabid et al., 2006), being produced and installed worldwide with 40 units fully operating, by more than 10 surgical teams (mainly in France).

The ceiling mounted 7 DoF robotised manipulator is based on a parallel delta mechanism (Fig. 2) and is mainly dedicated to endoscopy and biopsy procedures or neuronavigation applications (Briot et al., 2007). SurgiScope is particularly useful in intracranial operations when the procedure requires navigation between sensitive neural elements, visible through a restricted access (Benabid et al., 2006). Additionally, its neuronavigation function facilitates resections or targeting procedures when the boundaries of the surgical target volume are not visually distinct (Amin and Lunsford, 2004).

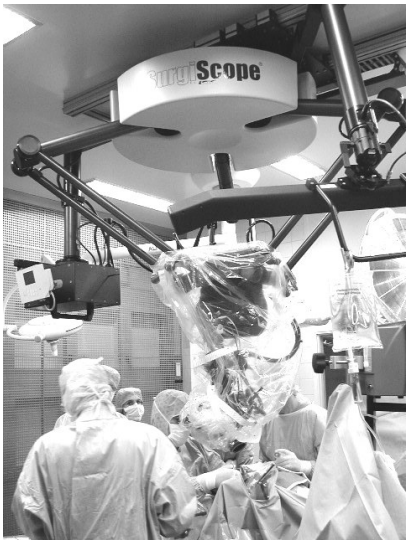


Fig. 2. ISIS Robotics SurgiScope (*Courtesy of ISIS Robotics*).

SurgiScope is the base for multiple integrable upgrade modules including: 1) an image import/conversion and treatment/planning software, 2) the microscope kit, 3) a handle set to single-handedly control the system motion, 4) a tool holder kit to position and hold surgical instrumentation, and 5) a head up display to display customised surgical plan data in the microscope oculars.

The preoperative targeting and trajectory planning are performed in the SurgiScope workstation (Lollis and Roberts, 2009). The patient's head is fixated to the operating bed through a Mayfield, and the registration between preoperative planning and intraoperative space is achieved with scalp fiducial markers using a handheld probe (Bekelis et al., 2012). After the craniotomy, the SurgiScope robot can operate in two modes. In the microscope mode, the robot that serves as a platform to operate a microscope. It aligns its optical axis with the predefined trajectory, and adjusts the microscope focal point to the surgical target. In the biopsy mode, an arm attachment with a probe carrier is attached to the robot. The Surgiscope robot then aligns its arm to the prescribed trajectory (Lollis and Roberts, 2009). Through the bushings of the robotically positioned stereotactic guide, the insertion needle is advanced to the planned target (Spire et al., 2008). Lollis and Roberts (2009) reports the application accuracy of Surgiscope as the mean distance from the catheter tip to the target to be 1.6 ± 3.0mm, in robotic placement of a central nervous system ventricular reservoir.

One of the biggest advantages of SurgiScope is the possibility to acquire and work with individual system modules, which permits surgical teams to avoid superfluous features and thus reduce the system cost. SurgiMedia, a modular platform to cope with SurgiScope multimedia part, guarantees system compatibility with any type of surgical material available, which further enhances the system flexibility. Extended operative time, acquisition costs and lack of mobility are considered to be the main drawbacks (Lollis and Roberts, 2009).

2) NeuroMate: NeuroMate (Renishaw-mayfield; Nyon, Switzerland) was the first neurosurgical robotic device to get CE mark in Europe and FDA approval in 1997 for stereotactic neurosurgical procedures (and in 1999 for frameless), thus being a major milestone and setting the standard (Haidegger et al., 2008) (Fig. 3). The NeuroMate works as an image-guided, passive assistant for holding, supporting and stabilising instrumentation controlled by the surgeon, increasing surgical safety and improving the surgery efficiency (Li et al., 2002; Varma and Eldridge, 2006). This robotic system shows appropriate mechanical stiffness, good accuracy and convenient workspace for stereotactic keyhole neurosurgery applications. Its advantages become even more evident in surgeries or biopsies that target multiple structures (Li et al., 2002; Xia et al., 2008). For a thorough explanation about a surgical workflow involving NeuroMate refer to (Cardinale et al., 2012).

It includes a kinematic positioning software, as well as a 5 DoF arm that achieves a technical accuracy of 0.7mm and a precision of 0.15mm, guaranteeing payload stability up to 7kg (Benabid et al., 1987; Varma and Eldridge, 2006). The neurosurgeon may choose to purchase the basic NeuroMate platform and acquire additional modules for frame-based, frameless and other functionalities on demand. Alternatively, the Neuromate system may be integrated in a custom workflow, coping with existing solutions (Cardinale et al., 2013; De Momi et al., 2013; Xia et al., 2008). Its design enables the use of conventional stereotactic localiser frames or an exclusive frameless method that resorts to an ultrasound system to register the robot's position relative to the patient's skull (Varma et al., 2003). Being developed strictly towards neurosurgery,

TABLE I
MOST SUCCESSFUL ROBOTIC SYSTEMS AND PROJECTS ORIENTED TO KEYHOLE TRANSCRANIAL STEREOTACTIC NEUROSURGERY.

	Project	Phase	Category	Institution	Main features
SPECIFIC	SurgiScope	Commercial use	Supervisory Controlled	ISIS Robotics, Saint Martin d'Hères, France	Delta parallel ceil mounted robotic manipulator with 7 DoF, modular architecture (user chooses the modules to work with)
	NeuroMate	Commercial use	Supervisory Controlled	Renishaw-Mayfield, Nyon, Switzerland	Serial robotic manipulator with 5 DoF, low-speed profile with sensor redundancy, mobile base, integrated planning system, frame/frameless ultrasound and CT-based registration
	Pathfinder	Experimental setup (Discontinued)	Supervisory Controlled	Prosurgics Ltd., High Wycombe, United Kingdom	Serial robotic manipulator with 6 DoF robot, mobile base, integrated planning system, frameless registration using fiducial markers
	Renaissance	Commercial use	Supervisory Controlled	Mazor Robotics Ltd., Caesarea, Israel	Hexapod parallel robotic manipulator with 6 DoF small and portable, directly mounted on the skull, integrated planning system, frameless and markerless, low-cost
	Robocast	Experimental setup (Project ended)	Supervisory Controlled, Telesurgical	NearLab, Politecnico di Milano, Milan, Italy	Serial, parallel and linear multi-robotic tele-operated system with $6+6+1$ DoF, mobile base and integrated planning system
	Rosa	Commercial use	Supervisory Controlled, Shared Control	MedTech SAS, Montpellier, France	Serial robotic manipulator with 6 DoF, low-speed profile, mobile base, integrated planning system, frameless registration, shared control manoeuvrability
ENABLED	MKM	Commercial use (Discontinued)	Supervisory Controlled, Telesurgical	Carl Zeiss, Oberkochen, Germany	Operating microscope mounted on a 6 DoF serial robotic manipulator for microscope navigation and tool guidance in biopsy applications
	NeuRobot	Experimental setup (Project ended)	Supervisory Controlled	Imperial College of Science, Technology and Medicine, London, United Kingdom	4 DoF rigid platform to hold and manipulate an endoscope around a pivot point, dynamical workspace constraint, frame reliant
	Evolution 1	Commercial use (Discontinued)	Telesurgical	Universal Robot Systems, Schwerin, Germany	4 DoF hexapod robot with tele-operated parallel actuator, mobile base, integrated planning system, for brain and spine applications
	neuroArm / SYMBIS	Experimental setup	Telesurgical	IMRIS, Winnipeg, Canada	Two 7 DoF tele-operated manipulators with an extra DoF due to the tool actuation mechanism, integrated with MRI technology for intraoperative instrumentation tracking

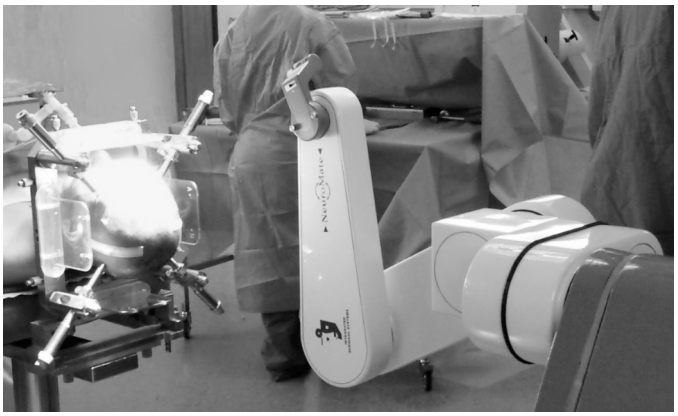


Fig. 3. Renishaw-Mayfield NeuroMate.

the NeuroMate has singular features that distinguish it from industrial robots like low speed, sensor redundancy and safety devices (Li et al., 2002; Varma and Eldridge, 2006).

Li et al. (2002) reports the NeuroMate's *in vitro* application accuracy using frame-based (0.86 ± 0.32mm) and frameless (1.95 ± 0.44mm) approach. It was concluded that there is no statistically significant difference between the frame-based traditional approach and NeuroMate's frame-based application accuracy. Other studies (Golash et al., 2000; Varma et al., 2003) validate and demonstrate the reliability of the frameless method against frame-based surgery. Cardinale et al. (2013) reports the *in vivo* localisation error of the NeuroMate frame-based approach in 91 SEEG procedures, to be 0.86 ± 0.54mm at the entry point and 2.04 ± 1.31mm at the target point. Recently von Langsdorff et al. (2014) studied the application accuracy (better than 1mm) of the NeuroMate frame-based approach *in vivo* for DBS electrode implantations.

On the negative side, the bulk robot structure and the system acquisition cost can be pointed. According to neurosurgeons, one desired upgrade would be to endow NeuroMate with drilling capabilities (Cardinale et al., 2013).

3) Pathfinder: The Pathfinder system (Prosurgics Ltd., High Wycombe, United Kingdom) (Fig. 4) is a robot built for neurosurgical procedures as a response to instrumentation miniaturisation and to the demand for further accuracy that, as stated by Eljamel (2007), will soon transcend even the most skilled surgeon capabilities. A 6 DoF robotic arm is installed on a mobile and stable platform to be easily moved around the operating room and firmly fixed to the Mayfied during surgery. One of Pathfinder trademarks are the fiducial markers (reflectors) attached to the patient's scalp or skull, and their continuous tracking using an embedded vision system to register the robot to the intraoperative space (Deacon et al., 2010). These markers consist of a black titanium sphere coated in a reflective material to be easily seen in CT scans and by

the camera system, respectively (Eljamel, 2007; Morgan et al., 2003).

Fig. 4. Prosurgics Pathfinder.

An initial CT exam is used to pinpoint the markers positions relative to the surgical volume, while the MRI dataset is required to segment the target brain structures. The CT and MRI datasets are then matched to overlay the targets and fiducial markers' locations. The Pathfinder planning software allows the neurosurgeon to view, edit and mark up medical images of the patient, and to plan the probe's trajectory (Finlay and Morgan, 2003). The Pathfinder can fixate itself to the Mayfield, opposite to the surgical side or at an acute angle parallel to the patient. By doing so, the robot can operate with some flexibility without interfering or obstructing the neurosurgeon's workspace (Eljamel, 2007).

Pathfinder frameless registration allows target acquisition with a millimetre accuracy (Finlay and Morgan, 2003). Furthermore, the robot can be repositioned within the operating room without the need to rescan or replan (Sivakumar et al., 2003). External fiducial markers allow the robotic system to constantly track its position relative to the patient, thus solving one of the biggest issues with preoperative image guided robots, and relieving the need for intraoperative online image scans (Deacon et al., 2010; Eljamel, 2007). The most reported problems with the Pathfinder system are: possible skin movements between preoperative scans and intraoperative, and registration failures caused by misidentification of markers due to abnormal lighting conditions (Eljamel, 2007).

Upon contacting the Pathfinder manufacturers we were told that this project terminated at the beginning of 2009 due to the lack of substantial funding and because of certification issues, and Prosurgics was later acquired by FreeHand 2010 Ltd.

4) Renaissance: The Renaissance robotic system (Mazor Robotics Ltd., Caesarea, Israel) originally developed for spine pedicle screw insertion by Prof. Shoham was adapted for keyhole minimally invasive neurosurgeries (Devito et al., 2010; Hu et al., 2013; Ringel et al., 2012). The system is composed by the MARS robot and controller, a custom robot base, a targeting guide and a registration jig. It is also accompanied by an "off-the-shelf" 3D laser scanner and a standard PC (Shoham et al., 2007). The system comprises 4 software modules: i) preoperative planning; ii) surface scan processing; iii) 3-way registration and iv) intraoperative execution. The system fits in the category of Supervisory Controlled, and serves mainly the purpose of tool guiding and drill assistance.

MARS is a small portable 6 DoF parallel robot ($5\times$ $8\times$ 8cm and a weight of 250g) with a motion accuracy of 0.1mm and resolution of 0.02mm (Fig. 5). The robot can be directly mounted on the patient's skull through the custom robot base, or mounted on a Mayfield. It is endowed with a lock mechanism, which is activated upon aligning the guide with the predefined entry point/target axis. The robot remains locked and rigid throughout the guiding and drilling phase, and is able to withstand lateral forces up to 10kg and actuation forces up to 1kg.

Fig. 5. Renaissance MARS robot (*Courtesy of Mazor Robotics, Inc.*).

The surgical procedure with the Renaissance system follows the premises of IGS. Initially a markerless and frameless CT/MRI scan of the patient is acquired, where the surgeon defines entry and target points, and the type of robot mounting (custom base or Mayfield) (Joskowicz et al., 2006). The registration between preoperative planning to intraoperative space is achieved through surface matching of the CT/MRI and laser scan cloud of points (Joskowicz et al., 2005; Shamir et al., 2005). The transformation between MARS robot base and the intraoperative space is computed based on a surface cloud of points containing both the registratrion jig (high relief wide-angle tetrahedron shape) and the patient's forehead or ear. The MARS robot now replaces the registration jig, and automatically positions its guide along the planned insertion trajectory. On surgeon demand, it automatically changes its guide position to a new trajectory (Joskowicz et al., 2006).

The Renaissance system surface registration error was reported to be close to 1mm, while the target registration error was around 1.7mm (Joskowicz et al., 2005, 2006; Shamir et al., 2005). Recently, a target registration error of 0.65mm was reported by Joskowicz et al. (2011) in a phantom study.

As a frameless and markerless system, Renaissance

overcomes the morbidity and head immobilisation requirements associated with stereotactic frames, eliminates the line-of-sight and tracking requirements of navigation systems and still provides a rigid platform for mechanical guidance without the bulk and costs of large robots. The system cost was initially aimed to be under 100k USD unlike other robotic solutions which range from 300k to 500k USD (Joskowicz et al., 2005, 2006).

5) Robocast: The Robocast – acronym for Robot and Sensor integration for Computer Assisted Surgery and Therapy project (FP7 ICT-2007-215190) – aimed to create a modular system to integrate image guided navigation and robotic devices for keyhole surgery (Fig. 6). The project developers pictured a human-robot interface with context-intuitive communication, embedded haptic feedback, a multiple robot chain with kinematic redundancy, an autonomous trajectory planner and a high level controller (Comparetti et al., 2011a; De Momi et al., 2009).

Fig. 6. Robocast robot (*Courtesy of De Momi, E. and Ferrigno, G. - Robocast Project*).

Robocast system consists of an optical and electromagnetic tracking system, ultrasound and three robotic actuators with haptic devices. The first robot, or *gross positioner*, is the Pathfinder robot with 6 DoF, there is another called *fine positioner*, which is the MARS (Renaissance) parallel robot with 6 DoF to further improve accuracy and the third is a linear piezo actuator to ensure linear insertion of electrodes or biopsy probes. The optical tracking system is used to *register* the intraoperative environment according to the preoperative plan. A single DoF haptic feedback actuator is used to control the probe depth (De Lorenzo et al., 2011).

The software platform can be divided in six subsystems: preoperative planning, human computer interface, sensor manager, high level controller, haptic controller and safety check (De Momi and Ferrigno, 2010). After the neurosurgeon selecting the target and entry area, the preoperative planning software autonomously calculates the lower risk optimal entry point and trajectory (De Momi et al., 2009, 2013). Human Computer Interface allows the surgeon to interact with the navigation system, while the sensor manager assembles data from the ultrasound and tracking system and inputs it to the system control centre. The high level controller manages information from the preoperative planning and sensor manager subsystems, and iteratively calculates the gross positioner and fine positioner kinematics (Comparetti et al., 2012). The haptic controller interfaces the linear actuator robot with the haptic device, transmitting a force-feedback reaction to surgeon for moving the probe. Finally, the safety check module runs regular state verifications in each subsystem and in case of failure it stops the probe movement (Comparetti et al., 2011b).

The technical accuracy of the iterative targeting approach based on continuous optical feedback was evaluated *in vitro*, in optimal and noise induced conditions. The largest reported translation median error was 0.6mm and 0.4mm for the entry and target points, respectively. While the largest rotation median error was 6.5×10^{-3}rad (Comparetti et al., 2012). The accuracy reported fits the requirements for clinical applications.

The Robocast project ended in 2011 and it is continued by the Active project - acronym for Active Constraints Technologies for Ill-defined or Volatile Environments (FP7-ICT-2009-6-270460) (Active Project, 2012; De Momi et al., 2014), which proposes an integrated redundant robotic platform that relies on two autonomous cooperating robotic manipulators for neurosurgery, which form a light and agile system with 20 DoF.

6) Rosa: The Rosa robotic system (MedTech SAS, Montpellier, France) is the latest generation of neurosurgical computer controlled robots for stereotactic surgery (Fig. 7). Rosa system comprises a mechatronic part consisting of a 6 DoF serial robotic manipulator and a control software part for neurosurgery planning, registration and guidance (Medtech S.A, 2012).

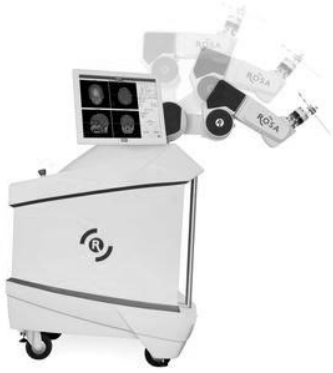


Fig. 7. Medtech Rosa (*Courtesy of Medtech Surgical*).

The planning software (Rosana, MedTech) allows merging different and complementary imaging techniques when studying the best surgical approach. The patient initially undergoes a MRI exam (with or without contrast, various supported sequences) to visualise the target anatomical structures, and to plan the optimal guiding trajectory (Gonzalez-Martinez et al., 2014; Serletis et al., 2014). This plan is then registered to a CT scan, performed near the time of surgery, which serves as the reference due to its homogeneous geometric accuracy. An intraoperative Flat-Panel CT can be integrated in the surgery

workflow to compensate for brain shift or robot registration errors (Lefranc and Le Gars, 2012; Lefranc et al., 2014a).

After uploading the plan to the Rosa system, the robot is firmly fixed to the skull clamp. The surgery team may choose to register the robot to the intraoperative scene in a frame-based (Leksell frame) or frameless approach. The frameless method is carried out using fiducial markers attached to the scalp/skull, or via the Rosa patented automatic surface scan. The latter combines robot motion and laser telemetry to provide a non-invasive registration (Lefranc et al., 2014b; Medtech S.A, 2010).

The robot is draped after a satisfactory registration and upon surgeon command, automatically moves to the planned guiding trajectory. It remains in a locked state while the entry point is marked and prepared. Scalp incision and skull drilling is performed with a cordless power drill (Gonzalez-Martinez et al., 2014). The neurosurgeon may choose to insert the probes or electrodes manually through the adapted reducers held by the arm, or use the haptic robot interface to lower the instruments (Lefranc et al., 2014a). This shared-control feature allows an intuitive interaction and control from the neurosurgeon with the tremor-less and motion restriction advantages.

Lefranc et al. (2014b) presents a study comparing different modalities of image and robot registration with a phantom and in actual procedures. Rosa system achieves an accuracy below 1mm for frame-based and fiducial registration, and a 1.22mm accuracy for frameless surface registration, both with CT as reference imaging[2].

The greatest asset of Rosa system when compared to the other solutions is its flexibility. It is easily integrable in the institution workflow and is reported to be well accepted (Lefranc et al., 2014a). No other robotic system offers these many options regarding robot registration. The Rosa system provides consistent and accurate instrument guidance while keeping surgery times comparable to conventional methodologies (Gonzalez-Martinez et al., 2014; Lefranc and Le Gars, 2012; Lefranc et al., 2014a). On the negative side, users point to the robot's learning curve and bulk dimensions, which limits the neurosurgeon's workspace.

B. Enabled for Stereotactic Neurosurgery

1) MKM: The MKM system (Carl Zeiss, Oberkochen, Germany) stands for "Multicoordinate Manipulator", and consists of three components: 1) an operating microscope mounted to 2) a 6 DoF motor-driven robotic arm, and 3) a computer workstation (Pillay, 1997). Its initial goal was to serve as a frameless stereotactic navigation system, by putting together the concepts of intraoperative microscopy and neuronavigation in minimally invasive IGS (Roessler et al., 1997).

The surgical procedure is planned based on preoperative image scans and registered to the intraoperative scene using scalp or bone fiducials. Inside the operating room, the neurosurgeon visualises the neuroimaging plan superimposed to the microscope optical field showing the entry point, target point, lesion contours and other structure markings (Pillay, 1997; Roessler et al., 1998). Several advantages arise from this fusion: the potential to outline and minimise the size and shape of skin incision, craniotomy and corticotomy; the capacity to decide between different surgical approaches and the possibility to perform more aggressive resections with lower risk of damaging nearby structures (Roessler et al., 1997).

Willems et al. (2001) extended the applicability of the MKM system by introducing an instrument holder for frameless stereotactic procedures to be mounted on the microscope. This instrument holder, also developed by Carl Zeiss, was an extension arm rigidly fixed to the microscope with a large channel for tool guidance. Plastic reducers are fit to the channel to constrain different instrumentation, for probe guidance or bone drilling (Willems et al., 2001). The MKM software was equipped with a "tool mode" module, which sets the instrument holder to align with the surgery planned trajectories, rather than the optical axis (Willems et al., 2003). Additionally, instead of tele-manipulating the microscope with a spherical sensor joystick, the microscope holder automatically moves to the predefined position (manual repositioning possible). During the instrument insertion, however, the system movements are disabled for safety reasons (Willems et al., 2001).

In vitro and *in vivo* studies were performed with the mounted instrument holder to assess the MKM system accuracy. Willems et al. (2001) reported slightly lower application accuracy with the robot when compared to the BRW frame, but a comparable target localisation error. Willems et al. (2003) reported an average biopsy localisation error of 3.3mm and 4.5mm depending on the registration method (bone screws or scalp adhesive fiducials). While acceptable for brain biopsy procedures, further accuracy is required for functional neurosurgery.

MKM system presents a fast, flexible and reliable alternative to stereotactic frames in biopsy brain surgeries and stereotactic neurosurgery guidance (Willems et al., 2001). On the other hand, the high acquisition costs, the bulky structure and the lack of mobility, are some of its negative features (Lefranc et al., 2014a; Willems et al., 2003).

2) NeuRobot: NeuRobot[3] was born from the European Community funded project ROBOSCOPE to provide a joint solution for common problems in Neurosurgery. The project involved a robotic arm (NeuRobot) and a simulator image-guided system, ROBO-SIM. Focusing on the robot platform, the NeuRobot is described by Auer et al. (2002) as "an active manipulator with inbuilt robotic capabilities" that includes: active constraint mechanisms of the manipulator motions based on mapped permitted regions, a precise pattern control and the capacity to automatically track moving features (Fig. 8).

The robotic manipulator has no more than 4 DoF to

[2]Surface registration with MRI scans are error prone due to image-related distortions, leading to significantly lower overall accuracy.

[3]Do not confuse with other system called NeuRobot (Hongo et al., 2003, 2006) that is a telecontroled micromanipulator system with a master-slave control hierarchy to perform minimally invasive procedures using an endoscope and three robotic arms. There is also another system also called NeuroBot, which is used in skull-based surgeries (Handini, 2004).

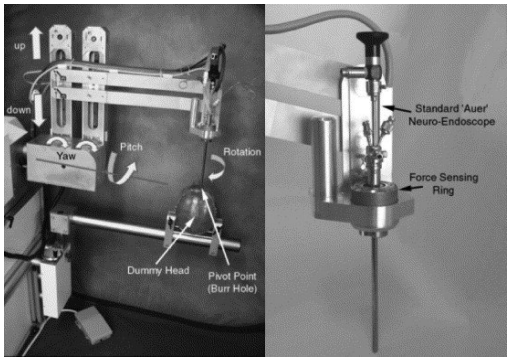


Fig. 8. NeuRobot (*Courtesy of Prof. Brian Davies, at Imperial College of London*).

manipulate instrumentation around a pivot point – the burr hole entry point in stereotaxy. These 4 DoF control the probe orientation around Yaw, Pitch, *Endoscope* rotation and the position along an *Endoscope* depth DoF, which implies that the NeuRobot can not reach the pivot point by itself and must, therefore, be previously positioned. This is one of the system's disadvantages because, if more than one trajectory is required, the robot needs to be repositioned and readjusted to the surgery table (Davies et al., 2000).

The manipulator includes a control mechanism developed from a flight-simulator experience by Fokker control systems b. v., it enhances precise motion and force-control using low force inputs (Auer et al., 2002). Special attention was given to safety issues. The system thus includes: dead man's switch and a workspace physically constrained in a safe operating volume based on MRI segmented data. An ultrasound imaging system is used to track tissue deformation during the procedure, and the probe position is dynamically compensated in real-time. The NeuRobot was able to operate autonomously, but it raised concerns about "who is in-charge" of the surgery (Davies et al., 2000).

Despite its advantages, the system is still dependant on a stereotactic frame to *register* the robot with the surgery reference (Davies et al., 2000). The robot was initially projected to hold and manipulate a neuroendoscope, but as stated by the authors it could in principle be used to handle other stereotactic instrumentation. One remarkable advantage of NeuRobot system is the integrated ROBO-SIM software, which enables the same manipulator to be used in real or simulated interventions to train and help neurosurgeons to become acquainted to the system (Auer et al., 2002).

3) Evolution 1: Evolution 1 robotic system (Universal Robot Systems, Schwerin, Germany) was especially designed for neurosurgical and endoscopic applications for micro scale brain and spine procedures. Different from the previous examples, Evolution 1 is a 4 DoF hexapod with a parallel actuator that combines high accuracy with great payload capacity. Its 6 mechanical parallel axes work as a spherical joint to move a platform with a slider mechanism that holds the endoscope. The parallel actuator approach enhances motion precision achieving an absolute positioning accuracy of $20\mu m$ and motion resolution of $10\mu m$, even under loads of up to $500N$ (Nimsky et al., 2004; Zimmermann et al., 2004).

Evolution 1 is able to compute the movement of all axes in less than 120μsec. It comprises an universal adapter enabling it to incorporate different types of surgical instrumentation like endoscopes and high speed drills. Due to the rather small working range, however, it must be pre-positioned in the desired orientation approximately 5cm above the entry point. Its user-interface is a touch screen and a master joystick device to control the end-effector motion and speed (Nimsky et al., 2004; Zimmermann et al., 2004).

Following IGS methodology, the end-effector instrumentation follows a trajectory set in preoperatively based on MRI scans and a planning software (VectorVision, BrainLab). Intraoperatively, the patient's face is scanned for surface recognition using infrared technology or laser surface scanning. Later this information is matched with preoperative MRI to guarantee that the robot knows its position relative to the surgery reference frame (Zimmermann et al., 2004).

The Evolution 1 main advantages are: high precision and steady positioning/manipulation of endoscope, smooth and slow movement execution within critical anatomical areas while handling surgical equipment. This system can be potentially adapted to assist stereotactic surgeries. However, a high payload capacity is superfluous since the instrumentation and the tasks are not weight demanding. Consequently, a parallel actuator is not always the best choice since it is typically large, restraining the neurosurgeon's workspace, and has a relatively small reach/flexibility.

4) neuroArm / SYMBIS: The awarded system neuroArm developed by Dr. Garnette Sutherland from the University of Calgary and engineers from Macdonald Dettwiler and Associates (MDA) was introduced in 2002, and was recently acquired and renamed SYMBIS (IMRIS, Winnipeg, Canada). The project's main goal is to take advantage of the MR-environment and haptic feedback technology, adding together 3D image reconstruction and high-end hand-controller design. It claims the title of the first image-guided, MR-compatible surgical robot capable of microsurgery and stereotaxy. It consists of two 7+1 DoF manipulators semi-actively actuated in a master-slave control type and moved by hand control at a remote workstation. The human-robot interface filters undesired hand tremors and can scale the movement of the controls relative to end-effectors (Pandya et al., 2009; Sutherland et al., 2008).

The neuroArm is built towards neurosurgery precision tasks, so each arm has a limited payload of $0.5kg$, force output of $10N$, a tip speed that ranges from 0.5 to $5mm/sec$ and a sub-millimetric accuracy. Patient safety was a paramount concern throughout the development of the robotic system, and features like active workspace constraints were added in case the robot leaves the safe operating zone. These policies granted neuroArm a Canadian Standards Association approval in 2007, Institutional Ethics and Investigational Testing approval by University of Calgary and Health Canada in 2008 (Fig. 9).

This robotic system is capable of microsurgery and stereotaxy which granted it the place among the enabled robotic platforms (Sutherland et al., 2003). Despite increasing the

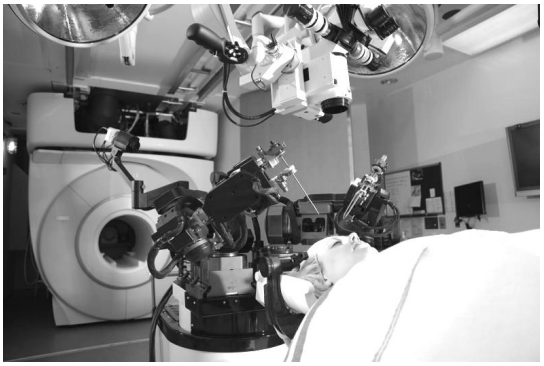


Fig. 9. University of Calgary neuroArm (*Courtesy of neuroArm Project, at University of Calgary*).

surgery time, its precision, steadiness and compatibility with a planning software resulted in reduced trauma and blood loss (Pandya et al., 2009). The end-effector positioning can be verified by overlaying 2D and 3D MRI information of preoperative and intraoperative, respectively. After positioning, a Z-Lock feature is used to restrict the tool motion along the defined longitudinal trajectory.

The main advantage of the neuroArm system is also a drawback in some stereotactic neurosurgeries, due to the need of a MRI scanning machine during the whole surgery with the associated maintenance and acquisition costs. Furthermore, the robotic system costs are also considerably greater since the robotic manipulator is manufactured exclusively using non-ferromagnetic materials (primarily titanium and polyetheretherketone) (Sutherland et al., 2008).

V. Current perspective and Future directions

If we compare the most successful robotic systems/projects for stereotactic procedures we find several similarities. All systems follow a very standard and similar surgical protocol related to the IGS paradigm. The main differences are mostly related to technical aspects.

Starting with the robot structure, most systems rely on serial instead of parallel actuators. The reason behind this tendency has to do with greater flexibility, compactness and broader workspace of serial manipulators when compared to parallel robots. Parallel robots excel at precision associated with larger payload requirements; even so, a larger payload capacity will seldom be a requirement in stereotactic procedures. It is important to remark the Renaissance system unorthodox solution, which takes advantage of the sturdiness of parallel actuators to miniaturise and create a portable robot. Although its narrow workspace prevents its use in SEEG applications, it can be used in DBS and biopsy surgeries.

The number of the manipulators' DoF vary between 4 and 7, except for the *Robocast* project's robot that follows a multi-robotic 13 DoF approach (for enhanced precision). The number of manipulation DoF affect not only the workspace but also the robot dexterity and flexibility, thus conditioning the surgical planning. Less DoF and smaller workspace means less flexibility, which directly influences how the robot should be placed to reach the planned trajectories and often implying obstructions to the medical team's workspace and vision of the surgical field. On the other hand, high dexterity and large manipulators – typically with more DoF – arise collision avoidance problems, all factors to be considered in the certification process.

Most of the robotic systems and projects for keyhole transcranial neurosurgery enable a frameless approach and are gradually detaching from the dependency on stereotactic frames. While frameless is one of the flags of robotic systems, the accuracy and repeatability of frameless systems is still surpassed by frame-based systems (Cardinale et al., 2013; Lefranc et al., 2014b). Specially for functional neurosurgery in deep-seated targets, frame-based is still the preferred solution because the frameless approach maximises accuracy and precision at the entry point rather than the target point, as in the arc-centred approach (Bjartmarz and Rehncrona, 2007; Zrinzo, 2012). Improving the efficiency and developing new frameless registration/fixation methods is a timely endeavour and a research opportunity.

The listed robotic systems converge in other aspects like the portability and embedded imaging and planning technology. The lack of mobility in systems like Surgiscope and MKM is held as a disadvantage. Being easy to transport and quick/easy to setup is certainly a premise for future robotic system developers. Additionally, the system modularity and possibility of choosing between different surgical approaches depending on the clinical case, greatly improves the system acceptance.

Safety is a paramount concern and should be addressed since the early stages system development (Taylor and Stoianovici, 2003). It is the most cited reason behind medical team's apprehension towards robotic technology (Lavallee et al., 1992). To achieve clinical clearance, a robotic system must at no single point of failure lead to loss of control and to injure the patient. Safety critical systems like these are typically endowed with redundant position encoders and mechanical limits for speed and exerted forces. Any sensory mismatch or consistency failure should cause the robot to *freeze* or go limp, while assuring a safe retract mechanism to resume the surgery in a traditional fashion (Talamini et al., 2003; Taylor et al., 2008). Regarding sterilisation, the system parts in direct contact with the patient must be either disposable or robust enough to withstand autoclaving or other sterilisation methods. Non-sterilised components need to be covered in sterile drapes or pre-sterilised bags (Taylor and Stoianovici, 2003). Lastly, the neurosurgeon can also be a source of errors, and thus must be carefully trained with the robotic system, and with the new procedure workflow involving the robot. Surgeons need to be instructed about the capabilities and limitations of the system, and become acquainted to the new surgical plan execution to check for any potential changes/problems (Taylor et al., 2008).

The most referred drawbacks of surgical robots are the high acquisition costs for hospitals and academic institutions (Mattei et al., 2014). One can argue that the passive behaviour expected of a robot assisting stereotactic surgery in manipulation and placement tasks are somewhat similar to industry tasks. An obvious choice would be to import industrial

technology to the operating room. Furthermore, the cost of a standard assembly robotic system is roughly half the price of a simple stereotactic frame. However, according to Davies (2000), for an industrial manipulator to comply with healthcare safety regulations, it should undergo several modifications which will further increase the robot costs. In any case, the major obstacles for the development of new surgical robotic systems can be attributed to: long and costly developments with little return; insurmountable walls of regulatory approvals or intellectual property legal battles (Gomes, 2011).

For new robotic platforms to achieve significant clinical acceptance, they should present unambiguous advantages over conventional approaches (Marcus et al., 2014; Taylor et al., 2008). The technological progress trend is currently oriented towards: miniaturisation and development of cost-effective robotic systems without sacrificing performance; and upgrading human-machine interfaces with enhanced haptic feedback and seamless integration with several imaging modalities in a surgically relevant yet intuitive way (Mattei et al., 2014; Motkoski and Sutherland, 2014).

VI. Conclusion

Surgical robots disclosure has already contributed significantly to an improved neurosurgical practice through increased precision, stability and the possibility to integrate state of art technology. The robotic solutions currently available for stereotactic surgeries can easily enhance the surgeons' performance relatively to standard surgery, and are becoming easier and more intuitive to use as this technology evolves. However, unfamiliarity with robot technology and the costs of the few commercially available solutions can discourage its use.

Closing the distance between physicians and engineers and promoting an active cooperation between both will be a key factor to improve robots for neurosurgery and encourage its use. Improvements in healthcare quality will ultimately surpass the inherent costs of surgery robotic systems, through less intraoperative lesions, shorter recovery and internment times.

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