Introduction and History of Robotics in Neurosurgery

Anton Fomenko, Fatima Ezzahraa El Idrissi, Narjiss Aji, Oumaima Outani, Kenza Benkirane, Hajar Moujtahid, Mohammed Maan Al-Salihi, and Demitre Serletis

1 Introduction

In the current era of the fourth industrial revolution, there is an increasing demand for digitization and automation, with corresponding changes arising in the healthcare landscape. Surgery, which calls for extreme precision and exactness, has particularly benefited from this transition, and robotic surgical techniques are now continually reshaping this field and redefining the ways in which surgeons treat their patients. The first surgical specialty to adopt robotic surgery was neurosurgery; in 1985, a stereotactic biopsy of a deep intracerebral lesion was performed with the guidance of a modified industrial robot, the Programmable Universal Machine for Assembly (PUMA) 200 robotic arm by Unimation [1, 2]. Since this introduction,

---

A. Fomenko
Section of Neurosurgery, Department of Surgery, Rady Faculty of Health Sciences, University of Manitoba, Winnipeg, MB, Canada
e-mail: fomenkoa@myumanitoba.ca

F. E. El Idrissi · K. Benkirane
Faculty of Medicine and Pharmacy of Fez, University of Sidi Mohamed Ben Abdellah, Fes, Morocco
e-mail: kenza.benkirane1@usmba.ac.ma

N. Aji · O. Outani · H. Moujtahid
Faculty of Medicine and Pharmacy of Rabat, Mohammed 5 University, Rabat, Morocco

M. M. Al-Salihi
College of Medicine, University of Baghdad, Baghdad, Iraq

D. Serletis (✉)
Department of Neurosurgery, Cleveland Clinic Foundation, Cleveland, OH, USA

Charles Shor Epilepsy Center, Neurological Institute, Cleveland Clinic, Cleveland, OH, USA

M. M. Al-Salihi et al. (eds.), *Introduction to Robotics in Minimally Invasive Neurosurgery*, https://doi.org/10.1007/978-3-030-90862-1_1

robotic technology has proved useful and has made its way successfully into the neurosurgical arena.

The field of neurosurgery is well suited to the implementation of robotic surgical techniques. The complex three-dimensional anatomy of the brain includes innumerable interconnected networks with over- and under-lying blood vessel arrays, all of which can be mapped on to a computerized coordinate reference system. The solid density of the skull encasing these delicate cerebral structures, when rigidly fixed in position, serves as a useful stationary reference point for registration and planning [3]. Moreover, the highly technical nature of neurosurgical procedures, including microsurgical approaches and the prolonged duration of cases, means that surgeons are susceptible to fatigue and undesirable tremors during lengthy procedures [4, 5]. It was therefore natural that robotic technology would eventually become established as an adjunct in neurosurgery.

Several different classification schemata are used in medical robotics, based on either the type of interaction between the robot and the surgeon, the technology of the robot itself, or its kinematic specifications. The following are three major categories, stratified by type of interaction with the surgeon [6, 7]:

1. Supervisory Control systems: Widely used in stereotactic and spine surgery, these devices move to a calculated position and reproduce a set of preprogrammed movements. Co-registration with CT and MR brain imaging allows an algorithm planned off-line by the surgeon to be executed autonomously by the robot [2]. The surgeon typically completes the remainder of the procedure without robotic assistance.
2. Dependent or Master–Slave systems: These are used in tele-neurosurgery or settings where the robot is located in challenging environments, and allow the neurosurgeon to maintain full control of the robot's movements in real time [8]. The surgeon receives a live view of the surgical scene via a monitor or eyepieces and manipulates linkage mechanisms online from a control station, which transmits commands to robotic manipulators in the remotely-situated operative suite.
3. Shared-Control systems: These are mixtures of active and passive systems where the surgeon directly interacts with the operative field rather than from a remote console. The clinician's movements are kinematically enhanced or filtered via the shared-control robot to achieve superior precision or haptic control [9].

In this chapter, we present an overview of the history and evolution of robotics in neurosurgery and its current landscape, with a focus on applications in stereotactic surgery and microneurosurgery.

2 The Evolution of Robotics in Stereotactic Surgery

The word "stereotaxy" is a combination of the Greek words *stereos*, meaning three-dimensional, and *taxis*, meaning arrangement [10]. Neurosurgery, as with other surgical disciplines, requires precision of any given intervention and minimization of harm to the patient. In general, stereotactic neurosurgical procedures involve several steps including application of a referential frame-based or frameless system, registration to patient-specific fiducials, and trajectory planning. In addition to the prolonged standing position in the operating theater, the manual setting, numerical input, calibration, and verification of coordinates can all contribute to human error and potential harm to the patient [5, 11]. To tackle those challenges, robotic assistance has been integrated naturally into the neurosurgical realm to improve efficiency of movement, target accuracy, and the overall safety profile of these procedures, among other important advantages [4, 12]. Robotic technologies are now integrated into several fields of neurosurgery including functional neurosurgery, pediatric neurosurgery, radiosurgery, endoscopic skull-base surgery, spine surgery, and epilepsy surgery [7, 13, 14]. A multitude of procedures now rely on such technologies including deep brain tumor biopsies, ventricular cannulation (including endoscopic third ventriculostomy), pedicle screw placement in spinal fixation, laser ablation procedures, deep intraparenchymal/intraventricular hemorrhage evacuation, deep brain stimulation (DBS), and stereoelectroencephalography (SEEG) electrode placement [6, 12].

Historically, localization of a given lesion in the cranium posed a particularly significant challenge. Despite early anthropological and phrenological conceptions, basic mathematical tools were combined with simple machines to generate the first attempts at craniocerebral topography [3]. During the 1860s, Pierre Paul Broca developed a range of special-purpose calipers such as the mandibular goniometer, along with the craniograph and stereograph, to locate essential skull landmarks such as the external occipital protuberance and the glabellum [3]. In 1903, Emil Theodor Kocher, a Swiss physician, developed a refined craniometer that could be applied to heads of various sizes and across any age group to locate intracranial structures such as the Sylvian fissure. This was later used by Harvey Cushing to locate craniocerebral targets [12]. In 1918, the first practical stereotactic frame based on Cartesian coordinates was developed by the mathematician Robert Henry Clarke and the neurosurgeon Sir Victor Alexander Hayden Horsley. It was later adapted for human use by the Canadian neuroanatomist Aubrey Mussen [15]. Although ahead of its time, Mussen's human stereotaxic prototype remained relatively unnoticed. It was not until important modifications to the Horsley-Clarke apparatus were made several decades later, by Henry T. Wycis and Ernest A. Spiegel, that frame-based human stereotactic surgery was formally established in 1947. This ultimately paved the way for the rapid emergence of stereotactic and functional techniques within the field of neurosurgery.

Over the ensuing decades, the emergence of innovative frameless systems and detailed neuroimaging modalities provided neurosurgeons with further possibilities. For example, the implementation of adherent radiolucent fiducials to the skin, or laser registration, has reduced the need for skull-mounted frames and rigid cranial fixation, improving flexibility and patient comfort. In parallel, the development of computed tomography (CT), followed by magnetic resonance imaging (MRI), has been essential for the stereotactic planning of modern-day non-invasive procedures, such as Gamma Knife radiosurgery and high-intensity focused ultrasound, by facilitating the precise targeting of specific brain regions [12].

Specifically focusing on robotic technology, the first robot in stereotactic surgery was the Unimation PUMA 200, used in 1985 to perform a CT-guided brain biopsy, which yielded diagnostic tissue on its first attempt. After proper calibration of the robot, an end-target accuracy of 1.0 mm (with 0.05–0.1 mm repeatability) and a shortened operative time (compared to unassisted frame-based biopsy) were demonstrated [12, 16]. Nevertheless, the lack of medical safety features and inability to compensate for intraoperative brain shift led to the PUMA 200 being discontinued from operative use following its pioneering demonstration [6].

After modern frameless registration with CT imaging was first demonstrated in 1986, robots especially suited for the neurosurgical suite were quickly developed [17]. These revolutionary systems included the Minerva (University of Lausanne, Lausanne, Switzerland); the Zeiss MKM surgical microscope (Carl Zeiss AG, Oberkochen, Germany); the NeuroMaster (Robotic Institute of Beihang University, Beijing, China); and the PathFinder Robot (Prosurgics, Wycombe, UK) [12]. Despite their limited clinical use, these systems spearheaded several important developments such as intraoperative imaging to correct for brain shift, redundant robotic kinematics, and no-go zones to minimize patient injury in the event of a malfunction.

Building on these developments, the neuromate (Renishaw) robot was the first to receive Food and Drug Administration (FDA) approval in 1997 and became the first device to offer both frame-based and frameless stereotactic registration. Early validation studies showed the accuracy of this system to be comparable to conventional manual frame-based and frameless techniques, while reducing operative time in multiple trajectory calculations [12, 18]. Still in active clinical use today, the neuromate has diversified robotic neurosurgery and has completed thousands of SEEG and DBS electrode placements, along with other neurosurgical procedures [12].

In contrast to the conventional robotic arm, the SurgiScope (ISIS SAS) is a ceiling-mounted surgical microscope with robotic capabilities developed in France during the late 1990s [19]. The SurgiScope was the first robotized platform to offer frameless, fiducial-based targeting with pre-operative MRI registration. Many SurgiScope (ISIS SAS) units have been installed worldwide, and the system is popular because of its modular nature and dual use as a microscope with trajectory overlay features.

First introduced by MedTech in 2012, the widely used and now modernized Robotic Stereotactic Assistant (ROSA, Zimmer Biomet) offers two separate platforms: the ROSA ONE Brain and Spine, each of which features built-in stereotactic trajectory assistance. The ROSA Brain has been installed in over 140 hospitals worldwide and utilized in diverse applications including laser ablation of epileptogenic foci, SEEG electrode insertion, shunt placement, cyst aspiration, and endoscopic procedures [12, 20, 21]. The ROSA Spine platform features capabilities such as trajectory assistance with cervical, thoracic, and lumbar transpedicular and vertebral body percutaneous screw placements.

More recently, the miniaturization of motors and electronics systems has allowed more compact, skull-mounted surgical robots to be developed such as the iSYS1

(Medizintechnik GmbH) and the Renaissance (Mazor Robotics) [12]. These robots are establishing themselves as cost-effective and efficient platforms that enable SEEG to be placed safely and accurately, although they require manual repositioning for contralateral-sided procedures. Furthermore, robotic surgical assistance is gaining traction in procedures benefiting from stereotactic trajectories that are customized to individual patient anatomy, such as endoscopic third ventriculostomies and endoscopic pituitary surgery. Platforms such as ROSA enable the surgeon to plan a patient-specific trajectory and simultaneously assist with tremor-free instrument stability and intraoperative trajectory corrections when required [13, 22].

Pediatric neurosurgery has its own distinctive operative challenges owing to the smaller targets and more fragile brains of infants and young children. The experience of using robotic technology in this patient population was well captured by De Benedictis et al. (2017), who assessed 116 children undergoing a series of 128 surgical procedures at the Bambino Gesù Children's Hospital (Rome, Italy) [23]. The authors reported the specific utility of the ROSA device in this young cohort, spanning several types of neurosurgical procedures including stereotactic biopsy, neuroendoscopy, DBS, SEEG electrode placement, and intracystic catheter placement. Only 3.9% of patients had transient postoperative deficits and none sustained any permanent deficit. This high success rate revealed the safety profile of robotic assistance in pediatric neurosurgical patients and demonstrated progressive reduction in operative time with increased system use. Additional prospective studies capturing larger numbers of patients and comparing end-target accuracy and other metrics, including quality of life and implant revision rates, are necessary to confirm these results [23].

A stroke-related procedure within neurosurgery, focusing on intracerebral hemorrhage (ICH) evacuation, has also benefited from robotic stereotactic innovation. Historically, these procedures would conventionally require a craniotomy to access a suitable cortical entry point for removal of a deep-seated hematoma. This invasive procedure has undergone innovations in recent times, facilitated by stereotactic-guided aspiration through a single burrhole. A recent systematic review compared the outcomes of three neuronavigation systems in minimally invasive ICH evacuation: Medtronic AxiEM, Stryker iNtellect, and BrainLab VectorVision [24]. The first of these systems is based on patient registration using electromagnetic stereotaxy, while the latter two are based on optical stereotaxy. Despite their technological differences and the inherent variations in registration, surgical planning, operative setup, and intraoperative use, all three systems were found to yield equivalent results and excellent accuracy for the procedure. The distinct advantages of pinless electromagnetic registration (AxiEM and iNtellect) include its versatility in cases where rigid skull fixation is contraindicated. In this way, the continuous progress of robotics in stereotactic surgery offers enhanced precision and a more conservative, less invasive approach for hemorrhagic stroke management [24].

In summary, over the past three decades, robotics have offered a significant technological contribution to the ever-evolving field of stereotactic neurosurgery, showing promising and safe results and addressing inherent challenges within complex neurosurgical procedures. Most notably, they have revolutionized the concepts of precision and accuracy, reproducibility, indefatigability, and endurance, all challenges faced by the modern-day neurosurgeon.

3 Robotics in Microsurgery

Microneurosurgery has evolved to include the neurosurgical microscope; miniaturized surgical instruments; and the delicate, minimally invasive and non-traumatic maneuvering required to access lesions of the nervous system. Theodore Kurze (1957) was the first neurosurgeon to use the microscope in the operating theater, for removing a neurilemoma of the seventh nerve in a five-year-old patient [25]. Among several subsequent pioneering neurosurgeons at that time, Professor Gazi Yaşargil is widely acknowledged as the most influential neurosurgeon to advance the field of microneurosurgery during the 1960s, developing techniques, microsurgical tools and approaches that have revolutionized the field ever since [26].

Fast-forwarding to the era of modern-day robotic technologies, a number of microsurgical robots have since been introduced into the operating theater. The Robot-Assisted Microsurgery System, or RAMS (NASA, Pasadena, CA), was one of the earliest examples. It comprised a 6-DOF (degrees of freedom) master–slave telemanipulator with programmable controls. In a feasibility study, ten rats underwent carotid arteriotomies in 1 mm diameter arteries that were later closed using either RAMS or the conventional manual technique [27]. The anastomoses were efficiently performed using RAMS, although the surgeons occasionally required external assistance while holding a needle or placing a suture with the robot. The accuracy, technical degree, and ratio error of RAMS and those of conventional techniques were similar. However, RAMS doubled the procedure duration [28, 29].

NeuRobot (Shinshu University School of Medicine, Matsumoto, Japan) was a telecontrolled micromanipulator system made of four main parts: a slave manipulator, a manipulator-supporting device, a master manipulator, and a three-dimensional display monitor [30]. A three-dimensional endoscope and three sets of micromanipulators, each with 3-DOF (rotation, neck swinging, and forward/backward motion), were connected to the slave manipulator. According to one report, NeuRobot was used clinically by neurosurgeons for the partial resection of brain tumors. However, the micromanipulators were limited to a restricted workspace of 10 cubic millimeters, resulting in limited maneuverability and frequent repositioning of the device for larger lesions [28, 29].

The Steady Hand System (Johns Hopkins University, Baltimore, Maryland) is another surgical robotic system developed for enhanced tool manipulation, and is one of the few shared-control surgical robotic systems to have been developed [9]. This device permitted the operator's hand movements to be refined with tremor-filtering functionality, resulting in smoother, dexterity-enhanced motion control of the instrument. Despite the novelty of this machine, the system could not be implemented into more complex interventions (such as anastomoses) owing to a lack of a dimensional scaling function. Despite its apparent benefits, implementation of this system was restricted to retinal microsurgery [6, 28, 29].

The da Vinci telesurgical system (Intuitive Surgical, Sunnyvale, California) is perhaps the most widely-adopted robotics system in medicine, yet its application in neurosurgery has been limited [31]. It comprises a master-slave system involving a stand-alone robotic tower and a master console. A binocular lens and camera system transmits magnified three-dimensional images of the surgical field to the surgeon's control panel, while two or three robotic instrument arms with 6-DOF allow for increased surgical dexterity [32]. A significant advantage of the da Vinci surgical system is the illusion of operating directly on the patient thanks to the anthropomorphic master console with integrated high-resolution twin eyepiece. The da Vinci robot has been used in several surgical fields, notably urology, but some groups have indicated its possible convenience in spinal surgery. To date, it has been used in resection of thoracolumbar neurofibromas, resection of paraspinal schwannomas, and anterior lumbar interbody fusions [33–35]. Because the system incorporates multiple robotic arms instead of a single shaft structure, there is a potential for arm collisions in confined working spaces or volumes. Thus, in narrow neurosurgical operative corridors, these limitations could diminish surgical workflow and therefore pose particular safety issues, limiting the use of the system in microneurosurgical procedures [14, 29].

A revolutionary neurosurgical system that began development in 2001 was the NeuroArm (University of Calgary, Alberta, Canada) [8]. Originally developed to be compatible within an open-bore MRI, it allows for real-time imaging of the surgical field during the procedure. The NeuroArm is a master–slave robot equipped with two robotic arms that can manipulate both conventional and specially-designed microsurgical instruments. The master control station features sensory immersion such as visual, auditory, and haptic feedback to the operator from a remote operative field. The manipulator's arms each have 8-DOF and two force sensors at their extremities. The system also includes end effectors that move in tandem with the operator's hand and can manipulate microsurgical instruments dexterously. It has since been successfully integrated into numerous clinical neurosurgical procedures in a graded fashion, highlighting the important contributions of robotic technology to precision and accuracy in the operating theater [8, 36]. The most recent innovation to the NeuroArm has been neuroArmPLUS^{HD}, which is a superior neurosurgery-specific haptic device with (7 + 2)-DOF and a serial linkage feature that increases system perceptiveness and is capable of simulating the human hand. A study comparing neuroArmPLUS^{HD} to other haptic devices such as Premium (6-DOF, serial linkage design) and Sigma 7 ((6 + 1)-DOF, parallel linkage design) showed that neuroArmPLUS^{HD} presented a higher level of performance for angular manipulation, procedure completion duration, force applied, number of clutches and distance covered [29, 37, 38].

In summary, modern-day advances in surgical robotic technology for microsurgery continue to unfold in an interdisciplinary fashion, relying on increased contributions from engineering, physics, and mathematics. Current systems such as the neuroArmPLUS^{HD} continue to push the frontiers of what robotic systems can offer to microneurosurgery. In particular, the positive effects on remote surgery, surgical precision, and accuracy, and tremor-free micro-manipulations, are paving the way toward increasingly safer approaches. Nevertheless, newly-emerging robotic systems in microsurgery must continue to address the critical constraints of safety, cost-effectiveness, learning curves in adoption, and space constraints in the operating theater [12, 39], among other limitations in the clinical environment.

4 Conclusions

Innovative technologies have brought a plethora of opportunities to the neurosurgical arena. Specifically, robotic neurosurgery can complement human shortcomings in neurosurgical procedures by diminishing tremors, improving safe surgical access to deep targets, automating serial operative steps, and refining geometric exactness. The contributions of robotic technology to stereotactic neurosurgical and microsurgical procedures continue to unfold and this technology is currently driving a paradigm shift in education and simulation for an entire generation of surgeons. These tools are providing neurosurgeons with greater versatility in exploring and performing more complicated procedures. When combined with future advances in telerobotic surgery and virtual/augmented reality systems, robotic technologies could revolutionize access to care for neurosurgical patients in underdeveloped regions with limited access to resources. There is therefore a clinical need for further refinement of future robotic systems, given the fragility of brain structures and the technical errors potentially inherent in the autonomous functionality of these machines, in a delicate environment where the neurosurgeon has small-to-zero margin of error. More research is required to develop these robotic technologies while concomitantly considering their safety profiles and cost-utilization in the operating theater.

References

1. Marcus HJ, Vakharia VN, Ourselin S, Duncan J, Tisdall M, Aquilina K. Robot-assisted stereotactic brain biopsy: systematic review and bibliometric analysis. Childs Nerv Syst. 2018;34(7):1299–309.
2. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. IEEE Trans Biomed Eng. 1988;35(2):153–60.
3. Serletis D, Pait TG. Early craniometric tools as a predecessor to neurosurgical stereotaxis. J Neurosurg. 2016;124(6):1867–74.
4. Wang MY, Goto T, Tessitore E, Veeravagu A. Robotics in neurosurgery. Neurosurg Focus. 2017;42(5):3171.
5. Fargen KM, Turner RD, Spiotta AM. Factors that affect physiologic tremor and dexterity during surgery: a primer for neurosurgeons. World Neurosurg. 2016;1(86):384–9.
6. Doulgeris JJ, Gonzalez-Blohm SA, Filis AK, Shea TM, Aghayev K, Vrionis FD. Robotics in neurosurgery: evolution, current challenges, and compromises. Cancer Control. 2015;22(3):352–9.
7. Nathoo N, Cavuşoğlu MC, Vogelbaum MA, Barnett GH. In touch with robotics: neurosurgery for the future. Neurosurgery. 2005;56(3):421–33. discussion 421–33
8. Sutherland GR, Wolfsberger S, Lama S, Zarei-nia K. The evolution of neuroArm. Neurosurgery. 2013;72(Suppl_1):A27–32.

9. Taylor R, Jensen P, Whitcomb L, Barnes A, Kumar R, Stoianovici D, et al. Steady-hand robotic system for microsurgical augmentation. Int J Robot Res. 1999;18(12):1201–10.
10. Grunert P, Keiner D, Oertel J. Remarks upon the term stereotaxy: a linguistic and historical note. Stereotact Funct Neurosurg. 2015;93(1):42–9.
11. Zrinzo L. Pitfalls in precision stereotactic surgery. Surg Neurol Int. 2012;3(Suppl 1):S53–61.
12. Fomenko A, Serletis D. Robotic stereotaxy in cranial neurosurgery: a qualitative systematic review. Neurosurgery. 2018;83(4):642–50.
13. Hoshide R, Calayag M, Meltzer H, Levy ML, Gonda D. Robot-assisted endoscopic third ventriculostomy: institutional experience in 9 patients. J Neurosurg Pediatr. 2017;20(2):125–33. Available from: https://thejns.org/pediatrics/view/journals/j-neurosurg-pediatr/20/2/article-p125.xml
14. D'Souza M, Gendreau J, Feng A, Kim LH, Ho AL, Veeravagu A. Robotic-assisted spine surgery: history, efficacy, cost, and future trends. Robot Surg. 2019;6:9–23.
15. Picard C, Olivier A, Bertrand G. The first human stereotaxic apparatus. The contribution of Aubrey Mussen to the field of stereotaxis. J Neurosurg. 1983 Oct;59(4):673–6.
16. Chen J, Chao L. Positioning error analysis for robot manipulators with all rotary joints. In: 1986 IEEE international conference on robotics and automation proceedings; 1986. p. 1011–6.
17. Roberts DW, Strohbehn JW, Hatch JF, Murray W, Kettenberger H. A frameless stereotaxic integration of computerized tomographic imaging and the operating microscope. J Neurosurg. 1986 Oct;65(4):545–9.
18. Li QH, Zamorano L, Pandya A, Perez R, Gong J, Diaz F. The application accuracy of the NeuroMate robot--a quantitative comparison with frameless and frame-based surgical localization systems. Comput Aided Surg. 2002;7(2):90–8.
19. Deblaise D, Maurine P. Effective geometrical calibration of a delta parallel robot used in neurosurgery. In: 2005 IEEE/RSJ international conference on intelligent robots and systems; 2005. p. 1313–8.
20. Lefranc M, Peltier J. Evaluation of the ROSA™ spine robot for minimally invasive surgical procedures. Expert Rev Med Devices. 2016;13(10):899–906. https://doi.org/10.1080/17434440.2016.1236680.
21. Brandmeir NJ, Savaliya S, Rohatgi P, Sather M. The comparative accuracy of the ROSA stereotactic robot across a wide range of clinical applications and registration techniques. J Robot Surg. 2018;12(1):157–63. https://doi.org/10.1007/s11701-017-0712-2.
22. Carrau RL, Prevedello DM, de Lara D, Durmus K, Ozer E. Combined transoral robotic surgery and endoscopic endonasal approach for the resection of extensive malignancies of the skull base. Head Neck. 2013;35(11):E351–8.
23. De Benedictis A, Trezza A, Carai A, Genovese E, Procaccini E, Messina R, et al. Robot-assisted procedures in pediatric neurosurgery. Neurosurg Focus. 2017;42(5):1–12.
24. Chartrain AG, Kellner CP, Fargen KM, Spiotta AM, Chesler DA, Fiorella D, et al. A review and comparison of three neuronavigation systems for minimally invasive intracerebral hemorrhage evacuation. J Neurointerv Surg. 2018;10(1):66–74.
25. Kriss TC, Kriss VM. History of the operating microscope: from magnifying glass to microneurosurgery. Neurosurgery. 1998;42(4):899–907. discussion 907–908
26. Hernesniemi J, Niemelä M, Dashti R, Karatas A, Kivipelto L, Ishii K, et al. Principles of microneurosurgery for safe and fast surgery. Surg Technol Int. 2006;15:305–10.
27. Le Roux PD, Das H, Esquenazi S, Kelly PJ. Robot-assisted microsurgery: a feasibility study in the rat. Neurosurgery. 2001;48(3):584–9.
28. Mitsuishi M, Morita A, Sugita N, Sora S, Mochizuki R, Tanimoto K, et al. Master-slave robotic platform and its feasibility study for micro-neurosurgery. Int J Med Robot. 2013;9(2):180–9.
29. Marcus HJ, Seneci CA, Payne CJ, Nandi D, Darzi A, Yang GZ. Robotics in keyhole transcranial endoscope-assisted microsurgery: a critical review of existing systems and proposed specifications for new robotic platforms. Neurosurgery. 2014;10(1):84–95.
30. Hongo K, Kobayashi S, Kakizawa Y, Koyama J-I, Goto T, Okudera H, et al. NeuRobot: telecontrolled micromanipulator system for minimally invasive microneurosurgery-preliminary results. Neurosurgery. 2002;51(4):985–8. discussion 988

31. Wang MY, Goto T, Tessitore E, Veeravagu A. Introduction. Robotics in neurosurgery. Neurosurg Focus. 2017;42(5):E1.
32. Wedmid A, Llukani E, Lee DI. Future perspectives in robotic surgery. BJU Int. 2011 Sep;108(6 Pt 2):1028–36.
33. Matveeff L, Baste JM, Gilard V, Derrey S. Case report: mini-invasive surgery assisted by Da Vinci® robot for a recurrent paravertebral schwannoma. Neurochirurgie. 2020;66(3):179–82.
34. Moskowitz RM, Young JL, Box GN, Paré LS, Clayman RV. Retroperitoneal transdiaphragmatic robotic-assisted laparoscopic resection of a left thoracolumbar neurofibroma. JSLS. 2009;13(1):64–8.
35. Lee JYK, Bhowmick DA, Eun DD, Welch WC. Minimally invasive, robot-assisted, anterior lumbar interbody fusion: a technical note. J Neurol Surg A Cent Eur Neurosurg. 2013;74(4):258–61.
36. Sutherland GR, Lama S, Gan LS, Wolfsberger S, Zareinia K. Merging machines with microsurgery: clinical experience with neuroArm. J Neurosurg. 2013;118(3):521–9.
37. Morita A, Sora S, Nakatomi H, Harada K, Sugita N, Saito N, et al. Medical engineering and microneurosurgery: application and future. Neurol Med Chir. 2016;56(10):641–52.
38. Baghdadi A, Hoshyarmanesh H, de Lotbiniere-Bassett MP, Choi SK, Lama S, Sutherland GR. Data analytics interrogates robotic surgical performance using a microsurgery-specific haptic device. Expert Rev Med Devices. 2020;17(7):721–30.
39. Fiani B, Quadri SA, Farooqui M, Cathel A, Berman B, Noel J, Siddiqi J. Impact of robot-assisted spine surgery on health care quality and neurosurgical economics: a systemic review. Neurosurg Rev. 2020;43(1):17–25. https://doi.org/10.1007/s10143-018-0971-z.