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Review Article

Robotics in neurosurgery: Current prevalence and future directions

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ABSTRACT

Background: The first instance of a robotic-assisted surgery occurred in neurosurgery; however, it is now more common in other fields such as urology and gynecology. This study aims to characterize the prevalence of robotic surgery among current neurosurgery programs as well as identify trends in clinical trials pertaining to robotic neurosurgery.

Methods: Each institution's website was analyzed for the mention of a robotic neurosurgery program and procedures. The future potential of robotics in neurosurgery was assessed by searching for current clinical trials pertaining to neurosurgical robotic surgery.

Results: Of the top 100 programs, 30 offer robotic cranial and 40 offer robotic spinal surgery. No significant differences were observed with robotic surgical offerings between geographic regions in the US. Larger programs (faculty size 16 or over) had 20 of the 30 robotic cranial programs (66.6%), whereas 21 of the 40 robotic spinal programs (52.5%) were at larger programs. An initial search of clinical trials revealed 223 studies, of which only 13 pertained to robotic neurosurgery. Spinal fixation was the most common intervention (six studies), followed by Deep Brain Stimulation (DBS, two studies), Cochlear implants (two studies), laser ablation (LITT, one study), and endovascular embolization (one study). Most studies had industry sponsors (9/13 studies), while only five studies had hospital sponsors.

Conclusion: Robotic neurosurgery is still in its infancy with less than half of the top programs offering robotic procedures. Future directions for robotics in neurosurgery appear to be focused on increased automation of stereotactic procedures such as DBS and LITT and robot-assisted spinal surgery.

Keywords: Robotic cranial, Robotic neurosurgery, Robotic spinal, Robotic assisted

INTRODUCTION

The last few decades have marked a rise in minimally invasive surgeries and greater incorporation of robotic assistance in surgical procedures. It is reported that the first application of robotics in surgery took place in the mid-1980s when the PUMA 560 robotic system was used to perform neurosurgical biopsy.[13] Medical robotics has progressed immensely since its origination. The current robotic systems available for surgery can be subdivided into three main categories:

active, semi-active, and master-slave.[12,23] Active systems work autonomously and conduct preprogrammed tasks while master-slave systems lack preprogramming and are solely dependent on surgeon input. Semi-active systems are a hybrid wherein surgeon input complements the system's preprogrammed elements.[13] Robotic systems provide surgeons with improved visualization, greater precision, and a reduction in fatigue.[26] However, concerns around hardware maintenance, cost, and sterilization pose some limitations to the incorporation of such systems.[18]

While the first instance of robotic-assisted surgery occurred in neurosurgery, robotics is now more common in fields with relatively less anatomical space constraints such as urology, gynecology, and orthopedics.[4,19,20,25] In general, robotic assistance in neurosurgery can particularly useful for procedures with very confined operative spaces: some applications of robots in neurosurgery include anatomical localization, stabilization of the surgeon's hand, anatomical planning for access to deep brain targets, and pedicle screw placement in spinal procedures.[7,18,29] Neuromate, Pathfinder, NeuroArm, SpineAssist, and Renaissance are among the robotic systems commonly used in neurosurgery.[1,18] Although robotic assistance may be more common in other surgical specialties, certain aspects of neurosurgery such as the microsurgical and technical nature of its procedures and its history of innovation in stereotaxy make it well-positioned for further incorporation of robotic assistance.[29]

Recently, there has been increased interest in robotic applications in neurosurgery as the demand for minimally invasive approaches to the brain and spine has grown. As new technologies continue to emerge, it is now possible to predict how neurosurgical robotics will progress in the coming years. This paper seeks to gauge the current prevalence of robotics in neurosurgical programs within the United States and assess future applications of robotics in neurosurgery through a review of ongoing clinical trials. We intend our report to provide key insight regarding current trends and future directions in neurosurgical robotics in a way that assists neurosurgeons in determining how they can optimize incorporation of this technology into their practice.

MATERIALS AND METHODS

Review of current neurosurgical programs

The US News and World Report's "Best Hospitals for Neurology and Neurosurgery" list was accessed in January 2022 to compile a list of the top 100 ranked neurosurgical hospitals in the United States. Each institution's website was analyzed for the mention of a robotic neurosurgery program and the provision of robotic neurosurgical procedures. Programs were, further, classified according to whether robotic spine surgeries and/or robotic cranial surgeries were available. The city and state of each program was collected and each program was classified into the appropriate geographical region (West, Midwest, Northeast, and South). Faculty size information of each program was also collected to determine if size of a program correlated with robotic surgery offerings. Programs were considered small if they had 15 or fewer faculty and large if they had greater than 15 faculties. The previous studies have found 16 faculty members as the median for neurosurgical programs.[24] These data were, then, analyzed to determine the number of programs offering robotic spine and robotic cervical surgery and the geographical spread of these programs.

Review of clinical trials

To assess the future potential applications of robotics in neurosurgery, an analysis of recent and ongoing clinical trials pertaining to neurosurgical robotic surgery was conducted. ClinicalTrials.gov,[2] a publicly available clinical trial registry, was queried in December 2021 with the following search criteria: (robot OR robotics OR robotic) AND (neurological OR neuro OR neurosurgery OR spine OR spinal OR brain OR neural OR hemorrhage OR stroke OR endovascular).

Of the resulting studies, those relevant to the application of robotics during neurosurgery-related procedures were retained for analysis. Trials related to postoperative rehabilitation and specialties other than neurosurgery were excluded from further analysis. The following information was collected from each relevant study record: condition(s) or disease(s) being studied, trial status, availability of study results, start date, projected trial duration, projected enrollment, number of sites clinical sites, sponsor type (industry, hospital/university, and NIH), and sponsor name. Each trial was also categorized by relevant clinical intervention based on the provided study description. These categories were as follows: "spinal fixation surgery," "deep brain stimulation (DBS)," "laser ablation," "cochlear implantation," or "endovascular embolization."

RESULTS

Neurosurgical program analysis

Of the top 100 ranked neurological surgery departments, 40 had robotic spinal programs and 30 had robotic cranial programs. The top 30 ranked programs accounted for 47.5% of the current robotic spinal programs and 60% of the current robotic cranial programs [Figure 1].

Robotic cranial and spinal surgery programs were evenly distributed across all geographic regions. The West had the lowest number of programs for robotic cranial surgery but

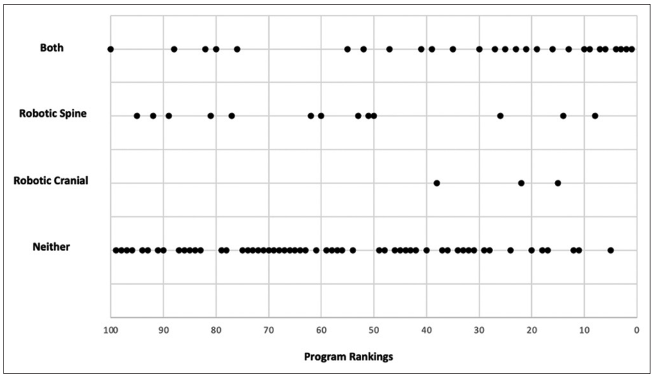

Figure 1: Rankings of the neurosurgical programs with robotic spinal or cranial surgery.

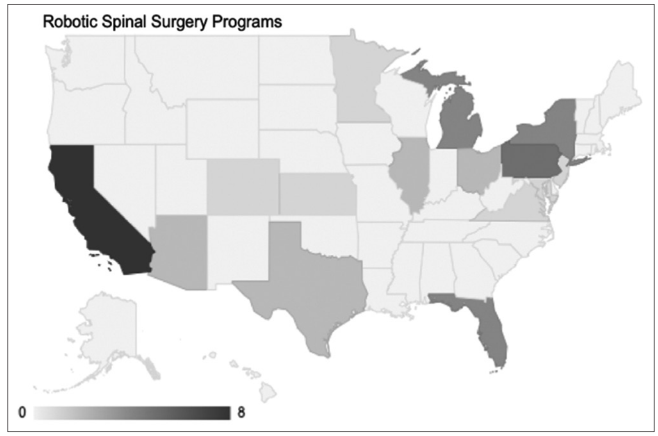

Figure 2: Geographical distribution of robotic spinal surgery programs.

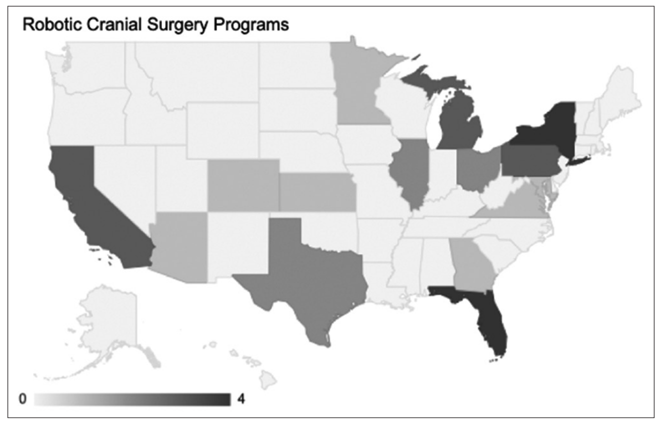

Figure 3: Geographical distribution of robotic cranial surgery programs.

the highest number of programs for robotic spinal surgery, at five and 11 programs, respectively. The South and Midwest both had nine robotic cranial surgery programs and nearly the same number of robotic spinal surgery programs, at nine and ten programs, respectively. The Northeast had seven robotic cranial surgery programs and 10 robotic spinal surgery programs.

There were 10 robotic cranial surgery programs with 15 or fewer faculty members and 20 programs with >15 faculty members. Nineteen robotic spinal surgery programs had 15 or fewer faculty members and 21 programs had greater than 15. These findings are summarized in Table 1.

California (three cranial and eight spinal) in the West, Michigan (three cranial and four spinal) in the Midwest, and Florida (four cranial and four spinal) in the South, all accounted for the most programs in both robotic cranial and spinal surgeries. New York (four cranial) in the Northeast had the most programs for robotic cranial surgery whereas Pennsylvania (five spinal) in the Northeast had the most programs for robotic spinal surgery [Figures 2 and 3].

Clinical trial analysis

The initial search of clinical trials yielded 223 results, of which 13 were relevant to this study [Figure 4]. In terms of the status of these studies, five were active and recruiting, three had not yet started to recruit, one was withdrawn, two were terminated, and two of the studies did not report their status. None of the 13 trials had been completed. As for trial duration, five of the studies projected a project length of <2 years and eight were >2 years. Six of the studies projected enrollment sizes of 100 or fewer participants and the other seven projected numbers greater than 100. Seven of the studies had one clinical site and the other six had more than one clinical site. Nine of the studies were industry sponsored and five of the studies were hospital sponsored. These findings are summarized in Table 2.

Table 1: Regional distribution and faculty size of robotic spinal and cranial surgery programs.

Characteristic	Robotic cranial surgery		Robotic spinal surgery	
	Number of programs		Number of programs	
	Yes	No	Yes	No
Region				
South	9	16	9	16
Northeast	7	19	10	16
Midwest	9	15	10	14
West	5	20	11	14
Total	30	70	40	60
Faculty size				
≤15	10	67	19	58
16+	20	3	21	2

Of the nine industry sponsored trials, five were distinct industry sponsors, with Mazor Robotics contributing the

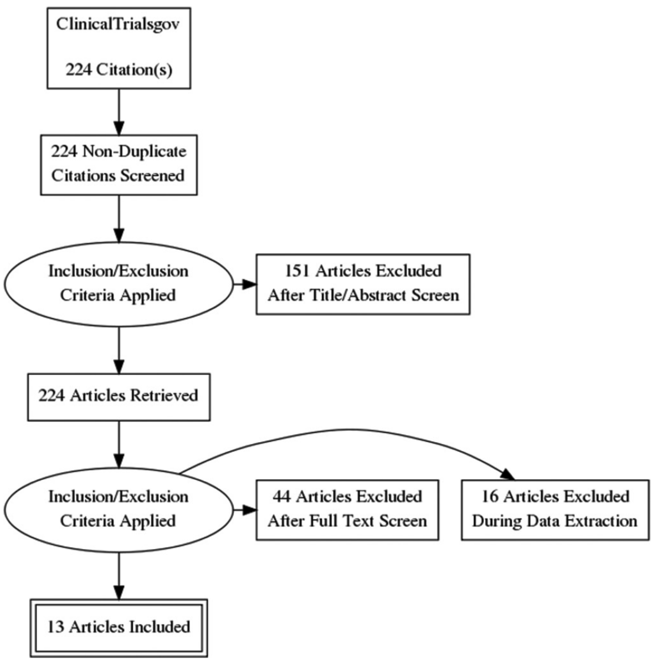

Figure 4: Flowchart of clinical trial analysis.

Table 2: Clinical trial status, enrollment size, duration, clinical sites, and sponsors.

Characteristic	
Status of clinical trials	Number of studies
Completed	0
Active/recruiting	5
Not yet recruiting	3
Withdrawn	1
Terminated	2
Unknown/not reported	2
Projected enrollment size	
≤100	6
101+	7
Projected trial duration	
<2 years	5
>3 years	8
Number of clinical sites	
1	7
2+	6
Industry sponsored	
N	4
Y	9
Hospital sponsored	
N	8
Y	5

most trials sponsored at four. All five of the hospital sponsored trials were conducted at different hospitals. One of the trials was sponsored by both hospital and industry. Having industry sponsors had no correlation with the status of the study [Table 3].

Of the 13 clinical trial studies, spinal fixation surgeries were the most common intervention. One out of the six spinal fixation surgery studies was hospital sponsored (the "EUROSPIN" study) and four were sponsored by Mazor Robotics. Studies that involved DBS and vertebral body augmentation intervention were all hospital sponsored. The study, "First Clinical Evaluation of HEARO Robotic Cochlear Implantation Surgery in Austria," was also hospital sponsored by the Medical University of Vienna. The rest of the studies for cochlear implantation, laser ablation, and endovascular embolization interventions were industry sponsored [Table 3].

DISCUSSION

The results of this study suggest that robotic usage in neurosurgery could still be in its infancy. Only 40 out of 100 neurosurgical departments have robotic spinal programs and 30 out of 100 departments have robotic cranial programs. While these robotic programs are evenly distributed across the US, they are more often seen in higher ranked institutions – the top 30 ranked neurosurgical programs controlled over 50% of the robotics market share. These findings aligned with the current trends within the literature as neurosurgery to date has not experienced mass adoption of robotics.

Furthermore, examination of future applications for robotics in neurosurgery through the clinical trial database showed a paucity of ongoing studies in this arena – only 13 relevant clinical trials were found to be applicable, none of which have been completed. These studies were also widely spread across a variety of neurological conditions, making it less possible to draw generalized conclusions about the progress of neurosurgical robotics across the field. In addition, industry was responsible for the most sponsors (69.23%) versus hospital sponsored clinical trials (38.46), which raises the potential of biases due to funding sources.

Having a larger program size, in terms of the number of faculty, also seemed to play some role in the adoption of robotic cranial surgery programs – most of these programs (67%) had more than 15 faculty members. This did not seem to apply to robotic spinal surgery programs; however, where the number of programs did not differ based on program size. Although further investigation is required to understand the reason for this disparity, it is possible that funding opportunities are simply more readily available for robotic spinal surgery programs, especially given the apparent industry enthusiasm for the incorporation of this technology. For example, of the six spinal fixation studies, five were industry sponsored, while studies involving deep brain fixation were solely hospital sponsored.

As evidenced by the results of this study, neurosurgery has not seen wide adoption in the usage of robotics despite the rich history of neurosurgical innovation in stereotaxy and brain localization, the highly technical nature of the

Table 3: Intervention, conditions treated, and sponsorship of clinical trials.

Intervention	Conditions treated	Study name	Sponsor
Spinal Fixation Surgery	Degenerative Disk Disease, Spondylolisthesis, Spondylosis, Scoliosis, Kyphosis, Kyphoscoliosis, Spinal Stenosis, Recurrent Disk Herniation, Spondylodiskitis, Spinal Tumor, Spinal Metastases	The European Robotic Spinal Instrumentation (EUROSPIN) Study	Marc Schröder, Bergman Clinics
		Mazor X Versus O-arm Navigation for Pedicle Screw Insertion	P. D. Dr. med. Duccio Boscherini, Neuro Orthopedic Center
		Prospective, Observational Registry of Renaissance-guided Spine Surgeries	Mazor Robotics
		Robotic versus Freehand Corrective Surgery for Pediatric Scoliosis	-
		ADDRESS – Adult Deformity Robotic versus Freehand Surgery to Correct Spinal Deformity	-
		MIS ReFRESH: Robotic versus Freehand Minimally Invasive Spinal Surgeries	-
Deep Brain Stimulation	Parkinson Disease, Dystonia, Essential Tremor	*In vivo* measurement of the accuracy of the “neurolocate” module of the neurosurgical robot “neuromate” in its application to deep brain stimulation	Centre Hospitalier Universitaire de Nice
		Optimization of VIM targeting in essential tremor surgery	University Hospital, Bordeaux
Laser Ablation	Metastatic Brain Tumor, Primary Brain Tumor, Epileptic/Seizure Foci, Movement Disorders	Laser ablation of abnormal neurological tissue using robotic NeuroBlate system	Monteris Medical
Vertebral Body Augmentation	Vertebral Body Augmentation	Robotic-assisted vertebral body augmentation – a radiation reduction tool	Hadassah Medical Organization
Cochlear Implantation	Sensorineural Hearing Loss, Deafness	Study of a minimally invasive cochlear access for cochlear implantation via a robotic procedure	MED-EL Elektromedizinische Geräte GesmbH
		First clinical evaluation of HEARO Robotic cochlear implantation surgery in Austria	Medical University of Vienna
Endovascular Embolization	Intracranial Aneurysm, Subarachnoid Hemorrhage, Headache	CorPath® GRX Neuro Study	Corindus Inc.

field, and the continued demand for minimally invasive procedures.[10,29] There are numerous indications for the use of robotics throughout neurosurgery. For example, there has been a rise in robot-assisted screw placement during spinal surgery, with multiple studies reporting the procedure to be safe and accurate.[14,15,27] In addition, this procedure has advantages over traditional surgery, including less exposure to radiation and fewer facet joint violations during screw placement.[11,17] Recent meta-analyses have also suggested that robotic assistance results in superior accuracy when compared to the conventional free-hand method.[9,16,22] These findings are supported by a randomized control trial which measured the accuracy and the clinical outcomes of robotic surgery compared to conventional techniques, and also found robotic surgery to be superior.[8] However, existing literature indicates that cost barriers associated with the initial purchase and yearly maintenance have prevented scalability across the neurosurgical specialty.[1,3,5,6] Neurosurgical robotics also requires a certain degree of mathematical literacy, posing barriers to an already congested healthcare system.[1] In addition, program chairs must consider the increased space requirements of robotic-assisted technologies along with technical failures that may be injurious to patients.[1,21,28]

The findings of this study must be seen in the light of some limitations. The novel SARS-CoV-2 (COVID-19) pandemic has impacted the practice of medicine, and neurosurgical programs may have outdated websites due to the unforeseen challenges of the COVID-19 pandemic. Therefore, assessing whether a neurosurgery program utilizes robotics using the information provided by its website, without official confirmation from the department chair, may provide incorrect data. In addition, regardless of the of COVID-19 pandemic, it is possible that some programs simply may not list the most up-to-date description of their robotic surgical services or may report offering certain services that are not currently available. Furthermore, using the clinical trials, database may leave out current trials outside of the United States that is not receiving funding from the National Institutes of Health. Future studies should incorporate searches using international clinical trial databases to present the current prevalence of robotics in neurosurgery across the world, or survey program faculty directly regarding the current status of robotic services at their institution.

Future studies could also survey current neurosurgical residents to assess how impactful the educational experience would become if neurosurgical robotics were incorporated within their curriculum. If strong desire exists, it may be the needed catalyst to drive the change required to move neurosurgery forward. Likewise, it may encourage leaders within the neurosurgical community to establish a fellowship program that gives programs without robotics an opportunity for residents to learn the symbiotic relationship between humans and machines.

CONCLUSION

Barriers and challenges still exist within the broad adoption of robotic assistance; however, if we ask the right questions, neurosurgery will continue to innovate as we enter the fourth industrial revolution.

Declaration of patient consent

Patient's consent not required as there are no patients in this study.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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