Neurointerventional Robotics: Challenges and Opportunities

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What is a “robot”?

The term “robot” first appeared in a 1920 play by the Czech writer Karel Čapek, titled R.U.R (Rossum’s Universal Robots) [1]. It was derived from the Czech word “robota”, which means servitude or forced labor. Although the word “robot” is nowadays widely used in everyday language, it is not clearly defined what we actually mean by it. The Robotic Institute of America has defined a robot as “a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or other specialized devices through various programmed motions for the performance of a variety of tasks” [2, 3]. Medical robotics account for 8% of all professional service robot sales, and with increasing popularity, worldwide sales figures increased by 20% from 2011 to 2013. This is mostly due to growing demands in the field of robot-assisted surgery [4], but medical robots are increasingly used for other purposes as well: some hospitals use cleaning robots which emit UV rays for instance, delivery robots transport meals and medication to patients’ rooms, and rehabilitation robots have been successfully integrated in many surgical and neurological rehabilitation programs [5]. In the field of neurointervention, robots are clearly on the rise: in the early months of 2020, 3 studies were published in rapid succession that showed safety and

feasibility of robot-assisted aneurysm coiling, [6] diagnostic angiography [7] and carotid stenting [7, 8], and leaders in the field are already thinking about how to create appropriate ethical and medicolegal frameworks [9] to ensure smooth and safe integration of robots into the neurointerventional workspace.

What are the Problems in Neurointervention that can be Solved with Robotics?

In order to appreciate the potential impact of robotics in improving neurointerventional care, one first has to understand the nature of the problems we are trying to solve with this technology, as well as its limitations. Defining design requirements and development prerequisites for the robotic environment is crucial to ensure result-oriented solutions. Broadly speaking, there are two advantages when using medical robots:

1. Remote control: enables spatial separation of the operator and the patient:
 - a. to ensure fast treatment for time-critical conditions, such as EVT for acute ischemic stroke as close as possible to the patient’s home.
 - b. to provide treatment by sufficiently skilled operators irrespective of the patient’s location.

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2. Enhancing human performance: autonomous decision making, automated correction and prevention of operator error.

Master-Slave Systems and Their Potential Applications

Teleoperated master-slave systems, in which the physician provides real-time input, and the robot executes the requested actions under direct supervision, as embodied by the da Vinci system (Intuitive Surgical, Sunnyvale, CA,

USA) have in part, defined surgical robotics. Other classifications include supervisory controlled (e.g. Rosa, Medtech, Zimmer Biomet, Montpellier, France) and shared control (Renaissance, Medtronic, Aliso Viejo, CA, USA), and Autonomous Systems (Autoguide, Medtronic). A teleoperated robot normally has a purely executive function, although autonomous functions, e.g. tool exchange, can be added to this paradigm. Table 1 outlines potential advantages, limitations and practical considerations when using master-slave robots for emergency procedures, such as EVT. These have to be put in the context of the currently limiting steps and whether current or near-future robot technology can over-

Table 1 Advantages and practical considerations of robot-assisted remote emergent therapy

Problem	Potential advantages of using robotics	Practical considerations
EVT treatment delays during nights and weekends [13] when travel times for the neurointerventional team are long	Remote EVT could help to reduce onset-to-treatment times by eliminating the travel time of the neurointerventional team	1) Robot has to be permanently kept in an “EVT-ready state” (no down-time) 2) Trained staff including technical engineer, to activate the robot and the necessary devices (catheters, stent-retrievers) have to be available on-site
Complete lack of access to EVT, particularly in smaller cities	1) Angiography suites are widely available (body intervention, cardiac cathlabs), but trained neurointerventional personnel is not. Robotics enables use of the available infrastructure to perform EVT even when a local neurointerventionalist is not available. 2) Stroke patients’ families prefer their relatives to be treated close to their hometown rather than in a distant hospital	1) Fast wireless connections and long distance image transfer are needed, but in many places the necessary infrastructure is not available yet [14]. Knowledge of delay and secure data storage platforms (cloud-based or other) need to be generated. 2) Trained staff and the engineer to activate the robot and the necessary devices (catheters, stent-retrievers) have to be available at the peripheral hospital. 3) Neurosurgery (for management of possible complications), anesthesia and post-EVT care facilities (intensive care unit) have to be available at the peripheral hospital. 4) The operator might not be familiar with the on-site equipment (e.g. small hospital with single plane angio unit because (s)he was trained at a big center exclusively on biplane units) 5) Responsibility for the patient has to be clearly defined: who manages postprocedural complications? To what degree should the remote operator be involved in post-EVT care?
Limited operator expertise in centers with low caseload/low call frequency	A skilled operator with sufficient experience and caseload could remotely perform EVT for several hospitals, and telemonitoring through experienced staff would be available on demand, so that safe, high quality treatment is ensured irrespective of patient location	1) High costs for installing and maintaining the robotic system: which hospital pays for it? 3) Patients might prefer a local operator (direct physician-patient contact)
Mental and physical physician burnout due to increased workload [15]	1) Robot-assisted interventions could reduce physical strain by reducing standing hours and radiation exposure (eliminating the need for lead aprons). 2) Robots could also reduce the physical strain during off-hours by eliminating repeated traveling to the hospital and allowing for telementoring by expert interventionalist, which would reduce junior operators’ stress levels	1) Risk of increased patient radiation dose due to reduced radiation dose awareness of the operator (could be mitigated by an automated built in radiation detection system). 2) High cost of providing off-site consoles

EVT endovascular therapy

come these limitations. For example, if the limiting steps are vascular or carotid access, then practical implementation of long distance EVT would have to be delayed until the robotic system is capable of performing these critical tasks. Investigators worldwide have taken on this challenge by incorporating ultrasound image guidance and simultaneous localization and mapping (SLM) into the procedure [10, 11]. While image guidance largely facilitates task completion, haptic feedback or the sense of touch, is well known to improve operator performance [3, 12].

Beyond Master-Slave Systems: Overcoming the Boundaries of Human Performance

One of the main advantages of a master-slave robotic system is the ability to quantify operator performance, e.g. which motions and degrees of freedom an operator uses when performing an endovascular task, which range of forces the operator exerts when maneuvering a catheter within the vascular lumen or pathology. Knowledge of such provides not only valuable information regarding the design requirements for the technology, but also avenues where automation and machine learning could enhance functionality and operator experience. The next frontier in medical robotics is designing robots with skills/functionality (ideally these skills should be acquired through analysis of procedures performed by expert neurointerventionalists), which could help human operators to overcome their limitations through enhanced fine coordination and integrated auto-settings for specific procedural steps or even complex task chains. Patient-specific simulation assistance is already available in the angiography laboratory, helping physicians to better plan the type and the size of the optimal device to be delivered, putting the physician behind the computer before starting EVT execution [16]. One may envision the robotic assistance as a logic continuation of this process, asking for a hyper-accurate therapeutic execution of the planned strategy by the machine itself: integrated force measurement systems and faster than human reaction times could allow for more steady and controlled navigation of catheters and avert complications [17]. When coiling an aneurysm, for instance, the microcatheter can get stuck at a vessel origin. Should forward force be applied, the catheter may suddenly jump forward, resulting in perforation of the aneurysm wall by the microwire. Humans, typically with an average reaction time of 0.2s, are usually unable to react fast enough to pull the microwire back and prevent this; robots with “super-human” reaction times (milliseconds) and motion feedback loops, however, could rapidly retract the wire and thereby prevent the perforation. This implies some form of machine learning allowing the robot to respond to incomplete data sets and based on

past experience anticipate the outcome, much similar to the human brain albeit with cumulative experience across thousands of experts and millions of data points. Another example is the degree of traction that can be applied to a microcatheter at the end of a long arteriovenous malformation embolization without rupturing the vessel: while it is often difficult for human operators to decide how much traction to apply, a robot that includes a haptic interface and data set from cumulative experience could include a ceiling on the traction force together with a force warning system [18]. This implies development of sensorized catheters with the sensor placement at or near the distal tip [19]. Image-guided systems with autopilot functions (similar to automated parking assist systems) could autonomously perform specific procedure steps and adapt their movements based on constant feedback from images and force sensors, thereby helping less experienced operators to manage difficult situations (e.g. navigation in tortuous vessel segments).

Robots also do not succumb to fatigue and can overcome human boundaries of precision, which allows for more accurate and reproducible placement of devices [20]. Operators would need to be trained in such a paradigm in order to become familiar with the technology, workspace, singularity, manipulability and the relationship to the remote manipulator to allow desired task completion [21]. In order to do so, it will become necessary for future operators to acquire simulator-based training prior to procedures as well as education for nuances and skillset [22]. The paradigm is comparable to the aviation industry, where completion of simulator-based training modules is a requirement prior to flying passengers, which indeed has transformed the industry to standardization of skill levels for improved safety and cost. In many centers across the world, simulator-based training is already successfully used in education programs for physicians and other healthcare professionals, enhancing their skillset and knowledge, and thereby ultimately improving patient outcomes [23]. Wide availability of neurointerventional robots could thus reduce human variance in performance by compensating for lack of experience and limited skills, thereby ensuring a uniformly high treatment quality. In the long run, it is quite possible that the new robotic environment will serve as a basis for innovations in treatment technology that are unforeseeable at the current moment. Furthermore, the robotic console itself can serve as a simulator and thereby enables “in vitro” training of operators prior to performing in-patient robotic interventions [24]. Fig. 1 shows how robotics could facilitate teleinterventions and improve human operator performance; graded by complexity and potential clinical impact.

Fig. 1 Exemplary potential applications of robotics to facilitate teleneurosurgery for EVT for acute ischemic stroke (blue) and to improve performance of human operators (green), graded by clinical impact and complexity. Similar principles apply to other time-critical conditions such as ruptured intracranial aneurysms. The semi-transparent boxes in the upper rows indicate an ideal state/future dream for consideration yet challenging to achieve in the foreseeable future. Accomplishing this state of autonomy will require accurate haptic feedback and simultaneous handling of multiple devices by the robot, which is currently not yet possible. Note that the x-axis and y-axis do not indicate a proportional increase in complexity and clinical impact

What are the Challenges of Implementing Robotics in Neurointervention?

While the idea of having remote control and super-expertise available on demand is interesting, several challenges will need to be overcome for this to become a reality. Besides the infrastructural and organizational challenges that are mentioned in Table 1, there are four fundamental questions the medical community has to agree upon prior to adapting robot-assisted approaches:

1. How can we know that we are improving treatment quality with robotics?
2. What is the medicolegal framework for robot-assisted interventions?
3. What are the ethical issues related to robot-assisted interventions?
4. Is such a paradigm shift cost-effective?

In order to answer question 1, objective performance metrics will need to be established to measure robot assisted treatment quality and compare it to conventional (non-robot assisted) treatment (what gets measured gets managed). The spectrum of robot-assisted treatment complications are different from conventional treatment approaches [25], and appropriate classification and reporting systems as well as effective management strategies for these complications are needed [26]. In most places, such systems are not implemented yet.

Second, medicolegal implications, issues of consent, reimbursement and licensing in the relevant jurisdiction will have to be dealt with. Similar to the marketing and operations of the da Vinci surgical system, regulatory bodies certifying companies that provide the robotic system will likely mandate that an interventionalist be present on site overseeing and mentoring remote interventions. This will be important to maximize the safety profile and ensure optimal outcome associated with the technology [27]. Given

the complexity of this situation it is plausible to consider the proposed telerobotic systems for electively performed procedures in the early phase, with a low periprocedural complication risk. Indeed, the first elective robot-assisted neurovascular interventions have already been performed [28]. The natural evolution, with continued mentoring and adoption of technology, could employ the concept of piggyback platforms, where the trainee neurointerventionalist at the remote site is linked to the expert through haptic devices. This would allow the expert to assume control of the procedure while the trainee learns in an immersive and intuitive environment. In addition, the learning curve and experience can be recorded and quantified [29–31].

Third, potential ethical concerns also have to be addressed. If remote robot-assisted treatment were to become clinical reality, there will need to be clear demonstration of noninferiority compared to the patient being transferred to the center of expertise. This noninferiority will have to extend beyond the immediate realm of the neurovascular procedure and also would need to include other aspects of patient care, such as anesthesia and postprocedural care. At the current moment, there is no hard evidence to suggest that robot-assisted treatment is noninferior to conventional care. Given this paucity of data, is it ethical to just treat patients with robot-assisted approaches in an exploratory manner, or should this exclusively be done in the framework of studies? Should all patients that underwent robot-assisted interventions be included in a registry? It is also unclear who would be responsible for maintaining such a registry and ensuring its completeness and data integrity. That said, these data would have extreme value for patient care, education, standardization of procedures, and, through machine learning, continue technology refinement-advancement.

Lastly, the cost-effectiveness of robot-assisted interventions will have to be taken into account. Sceptics might argue that the costs for maintaining and implementing a robotic system are high, but so are the potential savings: The per patient average healthcare and societal cost savings for achieving complete vs. near-complete reperfusion when performing EVT in acute ischemic stroke in the USA for instance are 10,000 and 20,000 US\$, respectively [32]. Similarly, the net monetary benefit for a 10 min decrease in time to treatment has been estimated to be 10,000 US\$ [33]. Remote EVT with telemonitoring through expert operators could potentially lead to substantial improvements in reperfusion speed and quality [34], thereby dramatically reducing downstream healthcare costs.

How can the Benefits of Robotics in Neurointervention be Maximized?

Robotics for neurointervention is in its infancy. Initial experience in highly controlled environments by skilled and experienced operators is promising. As with all new technologies, neurointerventional robots will be further developed and refined, and it is likely that they will find their way into clinical routine. The potential benefits of neurointerventional robots are tremendous, and so are the challenges of this technology. Maximizing the benefit from contemporary and future developments in robotic technology will require an understanding of current bottlenecks, leading to a comprehensive solution (e.g. a robot that can deploy and retrieve a stent-retriever may be of limited benefit if the bottleneck is carotid access). Sufficient operator training will need to be ensured through a comprehensive and standardized training curriculum. This is particularly important since the learning curve for any new technology is initially steep, and robotic-assisted interventions will be no exception [35, 36]. In parallel, issues surrounding patient care with periprocedural diligence, medicolegal aspects, cost containment and in particular data safety (collection, storage, management, analytics and usage/publication) will need to be duly addressed. Robotics and machine intelligence generate big data and hence pave the pathway to quantifiable metrics towards standardization. While challenging and convolute, none of these obstacles are insurmountable but rather present an opportunity, as reflected in the numerous ongoing initiatives and focus of laboratories and industries around the globe.

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Compliance with ethical guidelines

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Ethical standards For this article no studies with human participants or animals were performed by any of the authors. All studies performed were in accordance with the ethical standards indicated in each case.

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